Lesson 11

Design Review of Absorbers Used for Gaseous Pollutants

Goal

To familiarize you with the factors to be considered when reviewing absorber design plans for the permit process.

Objectives

At the end of this lesson, you will be able to do the following:

1. Explain the importance of the following factors in absorber design:

   - Exhaust gas characteristics

   - Liquid flow

   - Pressure drop

   - pH

   - Removal of entrained liquids

2. Estimate the liquid flow rate, the diameter, and the packing height of a packed tower using appropriate tables and equations

3. Estimate the number of plates and the height of a plate tower using appropriate tables and equations

Introduction

Gas absorbers are most often used to remove soluble inorganic contaminants from an air stream. The design of an absorber used to reduce gaseous pollutants from process exhaust streams involves many factors including the pollutant collection efficiency, pollutant solubility in the absorbing liquid, liquid-to-gas ratio, exhaust flow rate, pressure drop, and many construction details of the absorbers such as packing, plates, liquid distributors, entrainment separators, and corrosion-resistant materials. These have been discussed in detail in the previous lessons.

The same three basic review approaches discussed for particle removal are applicable for gas absorber evaluation:

1. Empirical relationships based on historical data

2. Theoretical principles based on gas chemistry and physics

3. Pilot scale test data

The theoretical relationships for gas absorption have been well defined over the many years that gas absorption has been studied; however, they can be very complex and are dependent on the mechanical design of the scrubber. As with particulate scrubbers, empirical relationships and general rules of thumb are often used to evaluate absorber designs and there is no one easy set of equations to evaluate the design of all absorbers.

All wet scrubbing systems are able to collect both particulate and gaseous pollutants emitted from process exhaust streams. However, spray towers, plate towers, packed towers, and moving-bed scrubbers are most often used for gaseous pollutant removal. This lesson will focus on equations used to estimate liquid flow rate, the diameter and the height of a packed tower, and the diameter and number of plates used in a plate tower to achieve a specified pollutant removal efficiency.

In evaluating an absorption system, the reviewer can use the equations in this lesson to estimate critical operating parameters or component sizes, then supplement this information with operating information on the particular scrubber type from previous lessons to complete the review process.

Review of Design Criteria

The principal design criteria are the exhaust flow rate to the absorber, measured in units of m^3/min (ft^3/min, or acfm), and the gaseous pollutant concentration, measured in units of parts per million (ppm). The exhaust volume and pollutant concentration are set by the process exhaust conditions. Once these criteria are known, the vendor can begin to design the absorber for the specific application. A thorough review of the design plans should consider the factors presented below.

Exhaust gas characteristics - average and maximum flow rates to the absorber, and chemical properties such as dew point, corrosiveness, pH, and solubility of the pollutant to be removed should be measured or accurately estimated.

Liquid flow - the type of scrubbing liquid and the rate at which the liquid is supplied to the absorber. If the scrubbing liquid is to be recirculated, the pH and amount of suspended solids (if any) should be monitored to ensure continuous reliability of the absorbing system.

Pressure drop - the pressure drop (gas-side) at which the absorber will operate; the absorber design should also include a means for monitoring the pressure drop across the system, usually by manometers.

pH - the pH at which the absorber will operate; the pH of the absorber should be monitored so that the acidity or alkalinity of the absorbing liquor can be properly adjusted.

Removal of entrained liquid - mists and liquid droplets that become entrained in the "scrubbed" exhaust stream should be removed before exiting the stack. Some type of entrainment separator, or mist eliminator, should be included in the design.

Emission requirements - collection efficiency in terms of parts per million to meet the air pollution regulations; collection efficiency can be high (90 to 99%) if the absorber is properly designed. The agency review engineer can use the equations listed in this lesson to estimate the absorber removal efficiency, liquid flow rate, tower diameter, and packing height. However, these equations can only estimate these values, and they should not be used as the basis to either accept or reject the design plans submitted for the permit process.

Absorption

Absorption is a process that refers to the transfer of a gaseous pollutant from a gas phase to a liquid phase. More specifically, in air pollution control, absorption involves the removal of objectionable gaseous pollutants from a process stream by dissolving them in a liquid.

The absorption process can be categorized as physical or chemical. **Physical absorption** occurs when the absorbed compound dissolves in the liquid; **chemical absorption** occurs when the absorbed compound and the liquid (or a reagent in the liquid) react. Liquids commonly used as solvents include water, mineral oils, nonvolatile hydrocarbon oils, and aqueous solutions.

Some common terms used when discussing the absorption process follow:

Absorbent - the liquid, usually water, into which the pollutant is absorbed.

Solute, or **absorbate** - the gaseous pollutant being absorbed, such as SO_2, H_2S, etc.

Carrier gas - the inert portion of the gas stream, usually air, from which the pollutant is being removed.

Interface - the area where the gas phase and the absorbent contact each other.

Solubility - the capability of a particular gas to be dissolved in a given liquid.

Absorption is a *mass-transfer operation*. In absorption, mass transfer of the gaseous pollutant into the liquid occurs as a result of a concentration difference (of the pollutant) between the liquid and gas phases. Absorption continues as long as a concentration difference exists where the gaseous pollutant and liquid are not in equilibrium with each other. The concentration difference depends on the solubility of the gaseous pollutant in the liquid.

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Absorbers remove gaseous pollutants by dissolving them into a liquid called the absorbent. In designing absorbers, optimum absorption efficiency can be achieved by doing the following:

- Providing a large interfacial contact area

- Providing for good mixing between the gas and liquid phases

- Allowing sufficient residence, or contact, time between the phases

- Choosing a liquid in which the gaseous pollutant is very soluble

Solubility

Solubility is a very important factor affecting the amount of a pollutant, or solute, that can be absorbed. Solubility is a function of both the temperature and, to a lesser extent, the pressure of the system. As temperature increases, the amount of gas that can be absorbed by a liquid decreases. From the ideal gas law: as temperature increases, the volume of a gas also increases; therefore, at the higher temperatures, less gas is absorbed due its larger volume. Pressure affects the solubility of a gas in the opposite manner. By increasing the pressure of a system, the amount of gas absorbed generally increases.

The solubility of a specific gas in a given liquid is defined at a designated temperature and pressure. Table 11-1 presents data on the solubility of SO_2 gas in water at 101 kPa, or 1 atm, and various temperatures. In determining solubility data, the partial pressure (in mm Hg) is measured with the concentration (in grams of solute per 100 grams of liquid) of the solute in the liquid. The data in Table 11-1 were taken from *The International Critical Tables*, a good source of information concerning gas-liquid systems.

Table 11-1.	Partial pressure of SO_2 in aqueous solution, mm Hg						
Grams of SO_2 per 100g H_2O	10°C	20°C	30°C	40°C	50°C	60°C	70°C
0.0	-	-	-	-	-	-	-
0.5	21	29	42	60	83	111	144
1.0	42	59	85	120	164	217	281
1.5	64	90	129	181	247	328	426
2.0	86	123	176	245	333	444	581
2.5	108	157	224	311	421	562	739
3.0	130	191	273	378	511	682	897
3.5	153	227	324	447	603	804	-
4.0	176	264	376	518	698	-	-
4.5	199	300	428	588	793	-	-
5.0	223	338	482	661	-	-	-

Solubility data are obtained at equilibrium conditions. This involves putting measured amounts of a gas and a liquid into a closed vessel and allowing it to sit for a period of time. Eventually, the amount of gas absorbed into the liquid will equal the amount coming out of the solution. At this point, there is no net transfer of mass to either phase, and the concentration of the gas in both the gaseous and liquid phases remains constant. The gas-liquid system is at equilibrium.

Equilibrium conditions are important in operating an absorption tower. If equilibrium were to be reached in the actual operation of an absorption tower, the collection efficiency would fall to zero at that point since no net mass transfer could occur. The equilibrium concentration, therefore, limits the amount of solute that can be removed by absorption. The most common method of analyzing solubility data is to use an equilibrium diagram. An **equilibrium diagram** is a plot of the mole fraction of solute in the liquid phase, denoted as x, versus the mole fraction of solute in the gas phase, denoted as y. (See Appendix A for a brief refresher on mole fractions.) Equilibrium lines for the SO_2 and water system given in Table 11-1 are plotted in Figure 11-1. Figure 11-1 also illustrates the temperature dependence of the absorption process. At a constant mole fraction of solute in the gas (y), the mole fraction of SO_2 that can be absorbed in the liquid (x) increases as the temperature decreases.
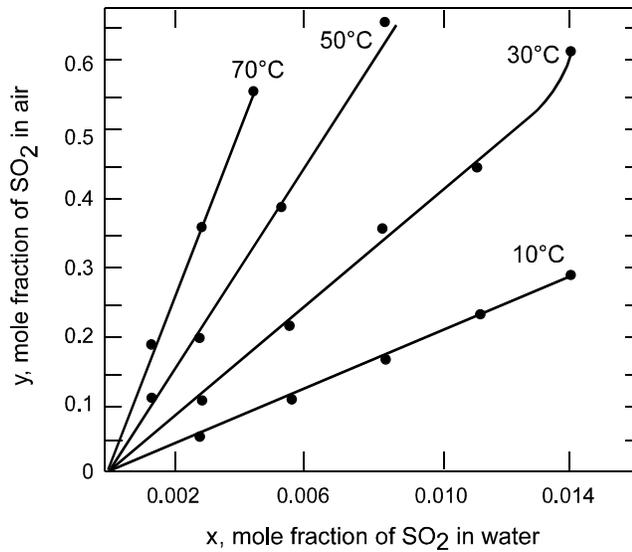
Figure 11-1.   Equilibrium lines for SO_2 - H_2O systems at
various temperatures

Under certain conditions, Henry's law may also be used to express equilibrium solubility of gas-liquid systems. **Henry's law** is expressed as:

$$p = Hx \qquad\qquad (11\text{-}1)$$

Where: p = partial pressure of solute at equilibrium, Pa
              x = mole fraction of solute in the liquid
              H = Henry's law constant, Pa/mole fraction

From Equation 11-1, you can see that H has the units of pressure per concentration. Henry's law can be written in a more useful form by dividing both sides of Equation 11-1 by the total pressure, P_T, of the system. The left side of the equation becomes the partial pressure divided by the total pressure, which equals the mole fraction in the gas phase, y. Equation 11-1 now becomes:

$$y = H'x \qquad (11\text{-}2)$$

Where: y = mole fraction of gas in equilibrium with liquid
          H' = Henry's law constant, mole fraction in vapor per mole fraction in liquid
          x = mole fraction of the solute in equilibrium

Note: H' now depends on the total pressure.

Equation 11-2 is the equation of a straight line, where the slope (m) is equal to H'. Henry's law can be used to predict solubility *only* when the equilibrium line is straight. Equilibrium lines are usually straight when the solute concentrations are very dilute. In air pollution control applications, this is usually the case. For example, an exhaust stream that contains a 1,000-ppm SO_2 concentration corresponds to a mole fraction of SO_2 in the gas phase of only 0.001. Figure 11-2 demonstrates that the equilibrium lines are still straight at this low concentration of SO_2.
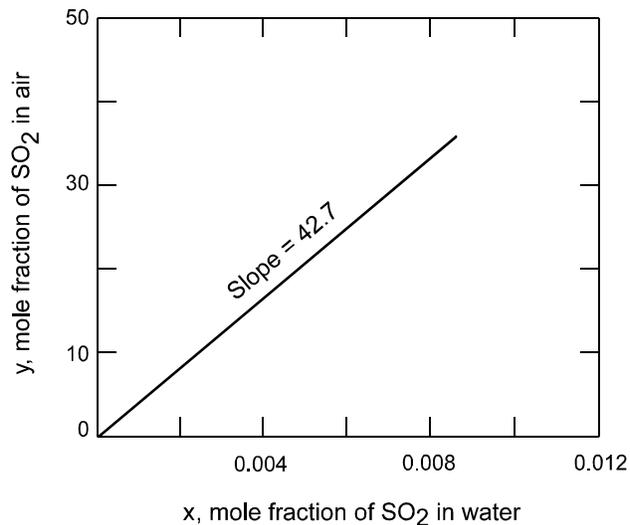
Figure 11-2.   Equilibrium diagram for SO_2 - H_2O system
               for the data given in Example 11-1

Another restriction on using Henry's law is that it does not hold true for gases that react or dissociate upon dissolution. If this happens, the gas no longer exists as a simple molecule. For example, scrubbing HF or HCl gases with water causes both compounds to dissociate in solution. In these cases, the equilibrium lines are curved rather than straight. Data on systems that exhibit curved equilibrium lines must be obtained from experiments.

Henry's law constants for the solubility of several gases in water are listed in Table 11-2. The units of Henry's law constants are atmospheres per mole fraction. The smaller the constant, the more soluble the gas. Table 11-2 demonstrates that SO_2 is approximately 100 times more soluble in water than CO_2 is.

Table 11-2. Henry's law constants for gases in H_2O[1]		
Gas	**20°C**	**30°C**
N_2	80.4	92.4
CO	53.6	62.0
H_2S	48.3	60.9
O_2	40.1	47.5
NO	26.4	31.0
CO_2	1.42	1.86
SO_2	0.014	0.016

1. Expressed in $H \times 10^{-5}$, atm/mole fraction.

The following example illustrates how to develop an equilibrium diagram from solubility data.

Example 11-1

Given the data in Table 11-3 for the solubility of SO_2 in pure water at 303°K (30°C) and 101.3 kPa (760 mm Hg), calculate y and x, plot the equilibrium diagram, and determine if Henry's law applies.

Table 11-3. Equilibrium data			
c_{SO_2} (g of SO_2 per 100 g of H_2O)	p_{SO_2} (partial pressure of SO_2)	y (mole fraction of SO_2 in gas phase)	x (mole fraction of SO_2 in liquid phase)
0.5	6 kPa (42 mm Hg)		
1.0	11.6 kPa (85 mm Hg)		
1.5	18.3 kPa (129 mm Hg)		
2.0	24.3 kPa (176 mm Hg)		
2.5	30.0 kPa (224 mm Hg)		
3.0	36.4 kPa (273 mm Hg)		

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Solution

In steps 1 and 2, convert the data for the concentration of SO_2 in water and the partial pressure of SO_2 in air into mole fraction units.

1. **Calculate the mole fraction of SO_2 in the gas phase, y**, by dividing the partial pressure of SO_2 by the total pressure of the system.

$$y = \frac{p_{so_2}}{P_T}$$

$$y = \frac{6 \text{ kPa}}{101.3 \text{ kPa}}$$

$$= 0.06$$

The mole fractions of SO_2 in the gas phase (y) are tabulated in Table 11-4.

2. **Calculate the mole fraction of the solute (SO_2) in the liquid phase, x**, by dividing the moles of SO_2 dissolved into the solution by the total moles of liquid.

$$x = \frac{\text{moles of } SO_2 \text{ in solution}}{\text{moles of } SO_2 \text{ in solution } + \text{moles of } H_2O}$$

Where: moles of SO_2 in solution $= c_{SO_2}/64$ g SO_2 per mole
moles of $H_2O = 100$ g of $H_2O/18$ g H_2O per mole $= 5.55$ moles

$$x = \frac{c_{so_2}/64}{c_{so_2}/64 + 5.55}$$

$$= \frac{\dfrac{0.5}{64}}{\dfrac{0.5}{64} + 5.55}$$

$$= 0.0014$$

The mole fractions of the solute in the liquid phase are tabulated in Table 11-4.

<table>
<tr><th colspan="4">Table 11-4.   Equilibrium data for Example 11-1</th></tr>
<tr><td>$c_{SO_2} = \dfrac{g\ of\ SO_2}{100\ g\ H_2O}$</td><td>$p_{SO_2}$
(kPa)</td><td>y = p/101.3</td><td>$x = \dfrac{c_{SO_2}/64}{c_{SO_2}/64 + 5.55}$</td></tr>
<tr><td>0.5</td><td>6.0</td><td>0.060</td><td>0.0014</td></tr>
<tr><td>1.0</td><td>11.6</td><td>0.115</td><td>0.0028</td></tr>
<tr><td>1.5</td><td>18.3</td><td>0.180</td><td>0.0042</td></tr>
<tr><td>2.0</td><td>24.3</td><td>0.239</td><td>0.0056</td></tr>
<tr><td>2.5</td><td>30.0</td><td>0.298</td><td>0.0070</td></tr>
<tr><td>3.0</td><td>36.4</td><td>0.359</td><td>0.0084</td></tr>
</table>

3. **Plot the mole fraction of SO_2 in air, (y), against the mole fraction of SO_2 dissolved in water, (x).**
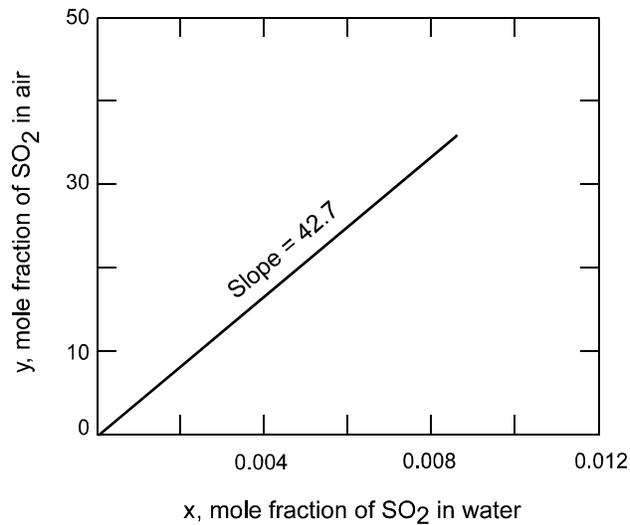
Figure 11-2.   (repeated) Equilibrium diagram for SO_2 - H_2O system for the data given in Example 11-1

The plot in Figure 11-2 is a straight line; therefore, Henry's law applies.

$$Slope = \frac{y}{x} = \frac{0.239 - 0.180}{0.0056 - 0.0042} \approx 42.7$$

The slope of the line ($\Delta y/\Delta x$), Henry's law constant (H'), is approximately equal to 42.7.

To test your knowledge of the preceding section, answer the questions in Part 1 of the Review Exercise.

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Absorber Design

Theory

The first step in designing an air pollution control device is to develop a mathematical expression describing the observed phenomenon. A valid mathematical expression describing absorber performance makes it possible to determine the proper absorber size for a given set of conditions, and predict how a change in operating conditions affects absorber performance. A number of theories, or models, attempt to analytically describe the absorption mechanism. However, in practice, none of these analytical expressions can solely be used for design calculations. Experimental or empirical data must also be used to obtain reliable results.

The most widely used model for describing the absorption process is the **two-film**, or **double-resistance**, theory, which was first proposed by Whitman in 1923. The model starts with the three-step mechanism of absorption previously discussed in Lesson 2. From this mechanism, the rate of mass transfer was shown to depend on the rate of migration of a molecule in either the gas or liquid phase. The two-film model starts by assuming that the gas and liquid phases are in turbulent contact with each other, separated by an interface area where they meet. This assumption may be correct, but no mathematical expressions adequately describe the transport of a molecule through both phases in turbulent motion. Therefore, the model proposes that a mass-transfer zone exists to include a small portion (film) of the gas and liquid phases on either side of the interface. The mass-transfer zone is comprised of two films, a gas film and a liquid film on their respective sides of the interface. These films are assumed to flow in a laminar, or streamline, motion. In laminar flow, molecular motion occurs by diffusion, and can be categorized by mathematical expressions. This concept of the two-film theory is illustrated in Figure 11-3.
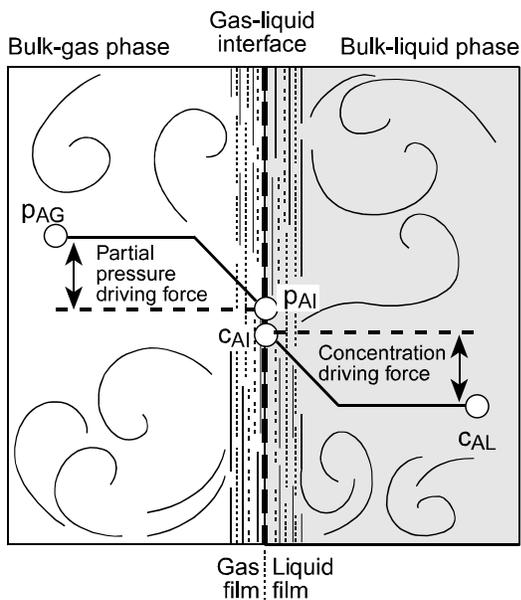
Figure 11-3.   Visualization of two-film theory

According to the two-film theory, for a molecule of substance A to be absorbed, it must proceed through a series of five steps. The molecule must:

1. Migrate from the bulk-gas phase to the gas film

2. Diffuse through the gas film

3. Diffuse across the interface

4. Diffuse through the liquid film

5. Mix into the bulk liquid

The theory assumes that complete mixing takes place in both gas and liquid bulk phases and that the interface is at equilibrium with respect to pollutant molecules transferring in or out of the interface. This implies that all resistance to movement occurs when the molecule is diffusing through the gas and liquid films to get to the interface area, hence the name *double-resistance* theory. The partial pressure (concentration) in the gas phase changes from p_{AG} in the bulk gas to p_{AI} at the interface.

A gas concentration is expressed by its partial pressure. Similarly, the concentration in the liquid changes from c_{AI} at the interface to c_{AL} in the bulk liquid phase as mass transfer occurs. The rate of mass transfer from one phase to the other then equals the amount of molecule A transferred multiplied by the resistance molecule A encounters in diffusing through the films.

$$N_A = k_g(p_{AG} - p_{AI}) \tag{11-3}$$

$$N_A = k_l(c_{AI} - c_{AL}) \tag{11-4}$$

Where: N_A =   rate of transfer of component A, g-mol/h•m^2
          (lb-mole/hr•ft^2)
        k_g =   mass-transfer coefficient for gas film, g-mol/h•m^2•Pa
          (lb-mole/hr•ft^2•atm)
        k_l =   mass-transfer coefficient for liquid film,
          g-mol/h•m^2•Pa (lb-mole/hr•ft^2•atm)
        p_{AG} =   partial pressure of solute A in the gas
        p_{AI} =   partial pressure of solute A at the interface
        c_{AI} =   concentration of solute A at the interface
        c_{AL} =   concentration of solute A in the liquid

The mass-transfer coefficients, k_g and k_l, represent the flow resistance the solute encounters in diffusing through each film respectively (Figure 11-4). As you can see from the above equations, as the value for a mass transfer coefficient increases, the amount of pollutant transferred (per unit of time) from the gas to the liquid increases. An analogy is the resistance electricity encounters as it flows through a circuit.
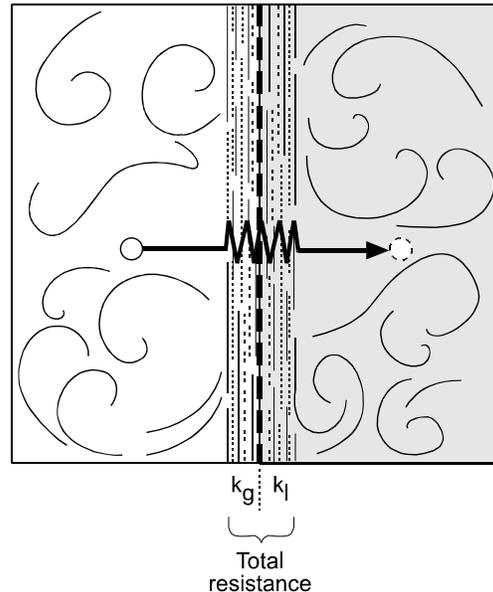
Figure 11-4.   Resistance to motion encountered by a
molecule being absorbed

Equations 11-3 and 11-4 define the general case of absorption and are applicable to both curved and straight equilibrium lines. In practice, Equations 11-3 and 11-4 are difficult to use, since it is impossible to measure the interface concentrations, p_{AI} and c_{AI}. The interface is a fictitious state used in the model to represent an observed phenomenon. Using the interface concentrations in calculations can be avoided by defining the mass-transfer system at equilibrium conditions and combining the individual film resistances into an overall resistance from gas to liquid and vice versa. If the equilibrium line is straight, the rate of absorption is given by the equations below:

$$N_A = K_{OG}\left(p_{AG} - p_A^*\right) \tag{11-5}$$

$$N_A = K_{OL}\left(c_A^* - c_{AL}\right) \tag{11-6}$$

Where: $N_A =$ rate of transfer of component, A, g-mol/h•m^2
(lb-mole/hr•ft^2)

$p_A^* =$ equilibrium partial pressure of solute A at operating conditions

c_A^* = equilibrium concentration of solute A at operating conditions

K_{OG} = overall mass-transfer coefficient based on gas phase, g-mol/h•m^2•Pa (lb-mole/hr•ft^2•atm)

K_{OL} = overall mass-transfer coefficient based on liquid phase, g-mol/h•m^2•Pa (lb-mole/hr•ft^2•atm)

p_{AG} = partial pressure of solute A in the gas

c_{AL} = concentration of solute A in the liquid

An important fact concerning Equations 11-5 and 11-6 is that they impose an upper limit on the amount of solute that can be absorbed. The rate of mass transfer depends on the concentration departure from equilibrium in either the gas (p_{AG} - p_A^*) or liquid (c_A^* - c_{AL}) phase. The larger these concentration differences are, the greater the rate of mass transfer becomes. If equilibrium is ever reached ($p_{AG} = p_a^*$ and $c_{AL} = c_A^*$) absorption stops and no net transfer occurs. Thus, the equilibrium concentrations determine the maximum amount of solute that is absorbed.

At equilibrium, the overall mass-transfer coefficients are related to the individual mass-transfer coefficients by the equations below.

$$\frac{1}{K_{OG}} = \frac{1}{k_g} + \frac{H'}{k_l} \tag{11-7}$$

$$\frac{1}{K_{OL}} = \frac{1}{k_l} + \frac{1}{H' k_g} \tag{11-8}$$

H' is Henry's law constant (the slope of the equilibrium). Equations 11-7 and 11-8 are useful in determining which phase controls the rate of absorption. From Equation 11-7, if H' is very small (which means the gas is very soluble in the liquid), then $K_{OG} \approx k_g$, and absorption is said to be **gas-film controlled**. The major resistance to mass transfer is in the gas phase. Conversely, if a gas has limited solubility, H' is large, and Equation 11-8 reduces to $K_{OL} \approx k_l$. The mass-transfer rate is **liquid-film controlled** and depends on the solute's dispersion rate in the liquid phase. Most systems in the air pollution control field are gas-phase controlled since the liquid is chosen so that the solute will have a high degree of solubility.

The discussion so far has been based on the two-film theory of absorption. Other theories offer different descriptions of gas molecule movement from the gas to the liquid phase. Some of the significant mass-transfer models follow. For these theories, the mass-transfer rate equation does not differ from that of the two-film method. The difference lies in the way they predict the mass-transfer coefficient. It has been shown that the rate of mass

transfer depends on a concentration difference multiplied by a resistance factor. Like most theories describing how something functions, absorption theories provide a basic understanding of the process, but due to the complexities of "real life" operations, it is difficult to apply them directly. Concentrations can easily be determined from operating (c and p) and equilibrium (c_A^* and p_a^*) data of the system. Mass-transfer coefficients are very difficult to determine from theory. Theoretically predicted values of the individual mass-transfer coefficients (k_g and k_l) based on the two-film theory, do not correlate well with observed values. Overall mass-transfer coefficients are more easily determined from experimental or operational data. However, the overall coefficients apply only when the equilibrium line is straight.

Mass-Transfer Models

The following discussion on mass-transfer models is taken from Diab and Maddox (1982).

Film Theory (Whitman 1923) - First, and probably the simplest theory proposed for mass transfer across a fluid. Details of this model are discussed in the text because it is the most widely used.

Penetration Theory (Higbie 1935) - Assumes that the liquid surface in contact with the gas consists of small fluid elements. After contact with the gas phase, the fluid elements return to the bulk of the liquid and are replaced by another element from the bulk-liquid phase. The time each element spends at the surface is assumed to be the same.

Surface-Renewal Theory (Danckwerts 1951) - Improves on the penetration theory by suggesting that the constant exposure time be replaced by an assumed time distribution.

Film-Penetration Theory (Toor and Marchello 1958) - Combination of the film and penetration theories. Assumes that a laminar film exists at the fluid interface (as in the film theory), but further assumes that mass transfer is a nonsteady-state process.

Mass-transfer coefficients are often expressed by the symbols $K_{OG}a$, k_la, etc., where "a" represents the surface area available for absorption per unit volume of the column. This allows for easy determination of the column area required to accomplish the desired separation. These mass-transfer coefficients are developed from experimental data and are usually reported in one of two ways: as an empirical relationship based on a function of the liquid flow, gas flow, or slope of the equilibrium line; or correlated in terms of a dimensionless number, usually either the Reynolds or Schmidt Number.

Figure 11-5 provides an example comparing the effect of two types of packing materials on the mass-transfer coefficient for SO_2 in water (Perry 1973). Packing A consists of one-inch rings and packing B consists of three-inch spiral tiles. As can be seen from this example, packing A has the higher transfer coefficient and would provide a better service in this application. Note that G' is the gas mass flow rate per cross-sectional area of tower (i.e. ft^2). Similar figures are used extensively to compare

different absorbers or similar absorbers with varying operating conditions. It should be noted that these estimated mass-transfer coefficients are system and packing-type dependent and, therefore, do not have widespread applicability. The *Chemical Engineers' Handbook* gives a comprehensive listing of empirically derived coefficients. In addition, manufacturers of packed and plate towers have graphs in their literature similar to the one in Figure 11-5.
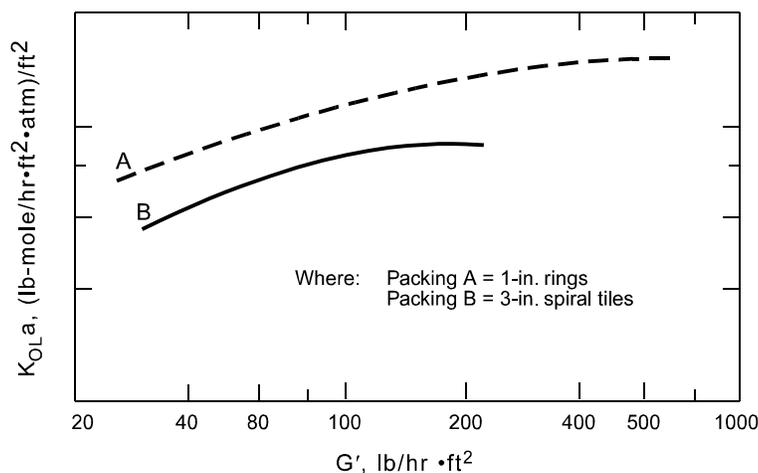
Figure 11-5.   Comparison of overall absorption coefficient for
SO$_2$ in water
Source: Perry 1973.

Although the science of absorption is considerably developed, much of the work in practical design situations is empirical in nature. The following sections will apply the principles discussed to the design of gas absorption equipment. Emphasis has been placed on presenting information that can be used to estimate absorber size and liquid flow rate.

To test your knowledge of the preceding section, answer the questions in Part 2 of the Review Exercise.

Procedures

The effectiveness of an absorption system depends on the solubility of the gaseous contaminant. For very soluble gases, almost any type of absorber will give adequate removal. However, for most gases, only absorbers that provide a high degree of turbulent contact and a long residence time are capable of achieving high absorption efficiencies. The two most common high-efficiency absorbers are plate and packed towers. Both of these devices are used extensively to control gaseous pollutants. Absorber design calculations presented in this lesson will focus on these two devices.

Numerous procedures are used to design an absorption system. These procedures range in difficulty and cost from short-cut "rules of thumb" equations to in-depth design procedures based on pilot plant data. Procedures presented here will be based on the

short-cut "rules of thumb." The approaches discussed in this lesson are for single component systems (i.e., only one gaseous pollutant).

When an absorption system is designed, certain parameters are set by either operating conditions or regulations. The gas stream to be treated is usually the exhaust from a process in the plant. Therefore, the volume, temperature, and composition of the gas stream are given parameters. The outlet composition of the contaminant is set by the emission standard which must be met. The temperature and inlet composition of the absorbing liquid are also usually known. The main unknowns in designing the absorption system are the following:

- The flow rate of liquid required

- The diameter of the vessel needed to accommodate the gas and liquid flow

- The height of absorber required to achieve the needed removal

Procedures for estimating these three unknowns will be discussed in the following sections.

Material Balance

In designing or reviewing the design of an absorption control system, the first task is to determine the flow rates and composition of each stream entering the system. From the law of conservation of mass, the material entering a process must either accumulate or exit. In other words, "what comes in must go out." A material balance helps determine flow rates and compositions of individual streams. Figure 11-6 illustrates the material balance for a typical countercurrent-flow absorber. The solute is the "material" in the material balance.
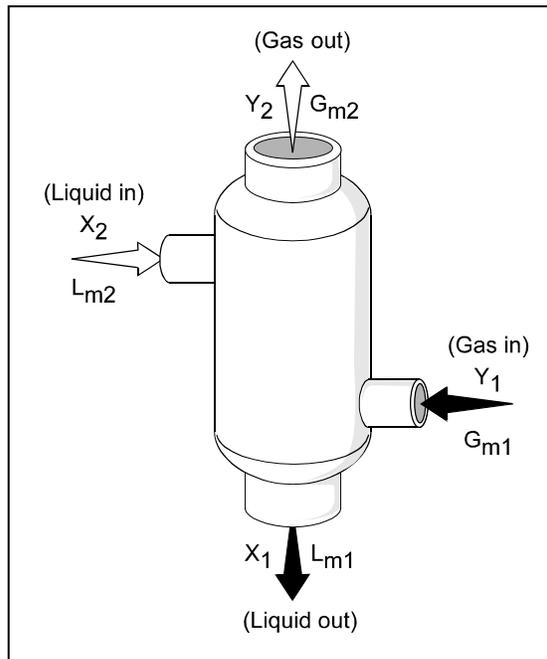
Figure 11-6.   Material balance for countercurrent-flow absorber

The following procedure to set up a material balance and determine the liquid flow rate will focus on a *countercurrent gas-liquid flow pattern*. This is the most common flow pattern used to achieve high-efficiency gas absorption. For concurrent flow, only a slight modification of this procedure is required. Equations for crosscurrent flows are very complicated since they involve a gradient pattern that changes in two directions. They will not be presented here.

$$X \; = \; \text{mole fraction of solute in pure liquid}$$
$$Y \; = \; \text{mole fraction of solute in inert gas}$$
$$L_m = \; \text{liquid molar flow rate, g-mol/h (lb-mole/hr)}$$
$$G_m = \; \text{gas molar flow rate, g-mol/h (lb-mole/hr)}$$

Engineering design work is usually done on a **solute-free basis** (X, Y) which means we ignore the amount of pollutant being transferred from the gas to the liquid. This makes the material balance calculations easier because we do not have to continually account for the change in mass of the flue gas as it is losing pollutant, or of the liquid as it is gaining pollutant. The solute-free basis is defined in Equations 11-9 and 11-10.

$$Y = \frac{y}{1-y} \tag{11-9}$$

$$X = \frac{x}{1-x} \tag{11-10}$$

In air pollution control systems, the percent of pollutant transferred from the gas to the liquid, y and x, is generally small compared to the flow of gas or liquid. Therefore, from Equations 11-9 and 11-10, $Y \approx y$ and $X \approx x$. In this lesson, it is assumed that X and Y are always equal to x and y respectively. If y (inlet gas concentration) ever becomes larger than a few percent by volume, this assumption is invalid and will cause errors in the material balance calculations.

An overall mass balance across the absorber in Figure 11-7 yields Equation 11-11.

$$\text{lb-mole in} = \text{lb-mole out} \tag{11-11}$$

$$G_m(in) + L_m(in) = G_m(out) + L_m(out)$$

For convenience, the top of the absorber is labeled as point 2 and the bottom as point 1. This changes Equation 11-11 to Equation 11-12.

$$G_{m1} + L_{m2} = G_{m2} + L_{m1} \tag{11-12}$$

In this same manner, a material balance for the contaminant to be removed is obtained as expressed in Equation 11-13.

$$G_{m1}Y_1 + L_{m2}X_2 = G_{m2}Y_2 + L_{m1}X_1 \qquad (11\text{-}13)$$

Equation 11-13 can be simplified by assuming that as the gas and liquid streams flow through the absorber, their total mass does not change appreciably (i.e., $G_{m1} = G_{m2}$ and $L_{m1} = L_{m2}$). This is justifiable for most air pollution control systems since the mass flow rate of pollutant is very small compared to the liquid and gas mass flow rates. For example, a 10,000-cfm exhaust stream containing 1,000 ppm SO_2 would be only 0.1% SO_2 by volume, or 1.0 cfm. If the scrubber were 100% efficient, the gas mass flow rate would change from 10,000 cfm at G_{m1} to 9999 cfm at G_{m2}. The transfer of a quantity this small is negligible in an overall material balance. Therefore, Equation 11-13 can be reduced to Equation 11-14.

$$G_m(Y_1 - Y_2) = L_m(X_1 - X_2) \qquad (11\text{-}14)$$

By rearranging terms, Equation 11-14 becomes Equation 11-15.

$$Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2) \qquad (11\text{-}15)$$

Equation 11-15 is the equation of a straight line. When this line is plotted on an equilibrium diagram, it is referred to as an **operating line**. This line defines operating conditions within the absorber: what is going in and what is coming out. An equilibrium diagram with a typical operating line plotted on it is shown in Figure 11-7. The slope of the operating line is the liquid mass flow rate divided by the gas mass flow rate, which is the liquid-to-gas ratio, or L_m/G_m. The liquid-to-gas ratio is used extensively when describing or comparing absorption systems. Determining the liquid-to-gas ratio is discussed in the next section.
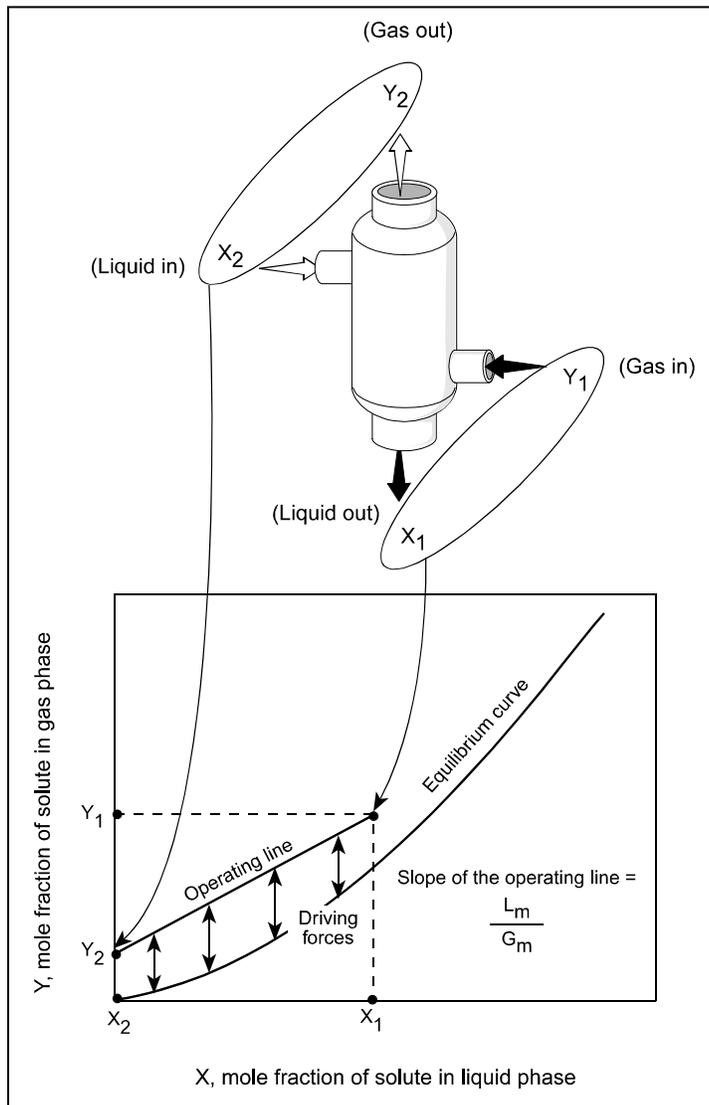
Figure 11-7.   Typical operating line diagram

Determining the Liquid Requirement

In the design of most absorption columns, the quantity of exhaust gas to be treated (G_m) and the inlet solute (pollutant) concentration (Y_1) are set by process conditions. Minimum acceptable standards specify the outlet pollutant concentration (Y_2). The composition of the liquid flowing into the absorber (X_2) is also generally known or can be assumed to be zero if it is not recycled. By plotting this data on an equilibrium diagram, the minimum liquid flow rate required to achieve the required outlet pollutant concentration (Y_2) can be determined.

Figure 11-8(a) is a typical equilibrium diagram with operating points plotted for a countercurrent-flow absorber. Point A (X_2, Y_2) represents the concentration of pollutants in the liquid inlet and the gas outlet at the top of the tower. At the minimum liquid rate, the inlet gas concentration of solute (Y_1) is in equilibrium with the outlet liquid concentration of solute (X_{max}). The liquid leaving the absorber is saturated with solute and can no longer dissolve any more solute unless additional liquid is added. This condition is represented by point B on the equilibrium curve.

In Figure 11-8(b), the slope of the line drawn between point A and point B represents the operating conditions at the minimum flow rate. Note how the driving force decreases to zero at point B. The slope of line AB is (L_m/G_m)min, and may be determined graphically or from the equation for a straight line. By knowing the slope of the minimum operating line, the minimum liquid rate can easily be determined by substituting in the known gas flow rate. This procedure is illustrated in Example 11-2.

Determining the minimum liquid flow rate, (L_m/G_m)min, is important since absorber operation is usually specified as some factor of it. Generally, liquid flow rates are specified at 25 to 100% greater than the required minimum. Typical absorber operation would be 50% greater than the minimum liquid flow rate (i.e., 1.5 times the minimum liquid-to-gas ratio). Setting the liquid rate in this way assumes that the gas flow rate set by the process does not change appreciably. Line AC in Figure 11-8(c) is drawn at a slope of 1.5 times the minimum L_m/G_m. Line AC is referred to as the **actual operating line** since it describes absorber operating conditions.
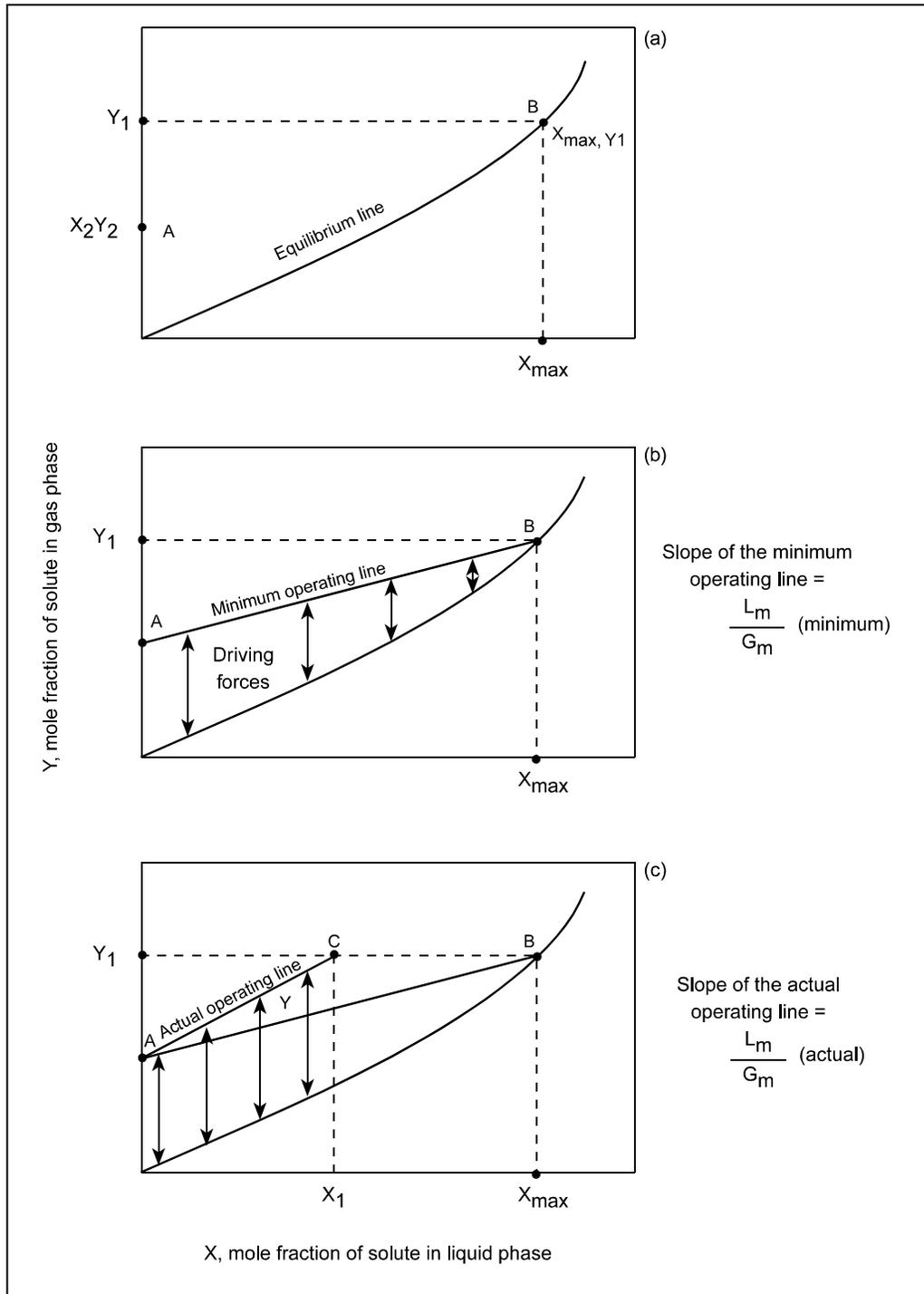
Figure 11-8. Graphic determination of liquid flow rate

The following example problem illustrates how to compute the minimum liquid rate required to achieve a desired removal efficiency.

Example 11-2

Using the data and results from Example 11-1, compute the minimum liquid rate of pure water required to remove 90% of the SO_2 from a gas stream of 84.9 m³/min (3,000 acfm) containing 3% SO_2 by volume. The temperature is 293°K and the pressure is 101.3 kPa.

Solution

1. **Determine the mole fractions of the pollutants in the gas phase, Y_1 and Y_2.** Then, sketch and label the drawing of the system as shown in Figure 11-9.

$$Y_1 = 3\% \ SO_2 \text{ by volume}$$
$$= 0.03 \text{ mole fraction of } SO_2$$

$$Y_2 = 90\% \text{ reduction of } SO_2 \text{ from inlet concentration}$$
$$= (10\%) \ (Y_1)$$
$$= (0.10) \ (0.03)$$
$$= 0.003 \text{ mole fraction of } SO_2$$
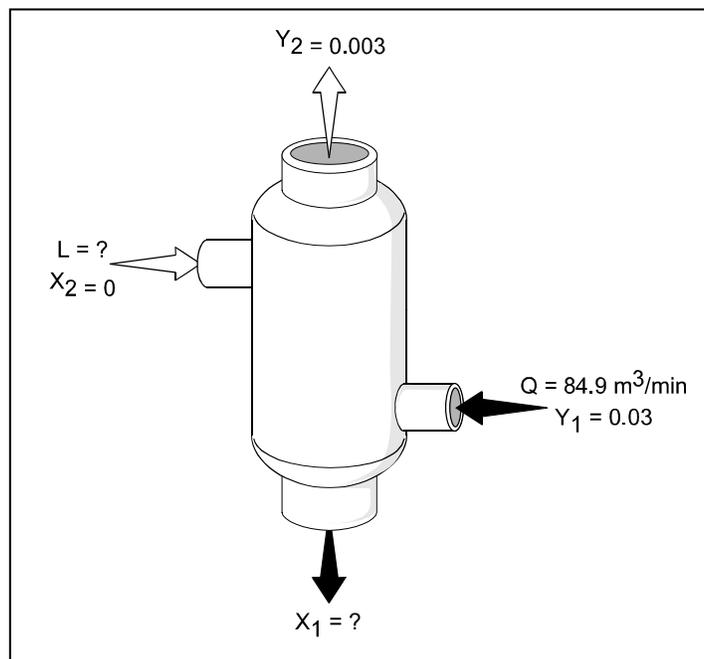
Figure 11-9.   Material balance for Example 11-2

2. **Determine the mole fraction of SO_2 in the liquid leaving the absorber to achieve the required removal efficiency.** At the minimum liquid flow rate, the gas mole fraction of pollutants going into the absorber, Y_1, will be in equilibrium with the liquid mole fraction of pollutants leaving the absorber, X_1, (the liquid will be saturated with SO_2). At equilibrium:

$$Y_1 = H' \ X_1$$

and Henry's law constant from Example 11-1 is

$$H' = 42.7 \frac{\text{mole fraction of } SO_2 \text{ in air}}{\text{mole fraction of } SO_2 \text{ in water}}$$

$$X_1 = \frac{Y_1}{H'}$$

$$= \frac{0.03}{42.7}$$

$$= 0.000703$$

3. **Calculate the minimum liquid-to-gas ratio** using Equation 11-15.

$$Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$$

Therefore,

$$\frac{L_m}{G_m} = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$\frac{L_m}{G_m} = \frac{0.03 - 0.003}{0.000703 - 0}$$

$$= 38.4 \frac{\text{g - mol of water}}{\text{g - mol of air}}$$

4. **Convert the exhaust stream flow rate, Q_G, to the exhaust gas molar flow rate, G_m** (from units of m³/min to units of g-mole/min). At 0°C and 101.3 kPa, there are 0.0224 m³/g-mole for an ideal gas.

First, convert the volume of gas from 0 to 20°C (from 273 to 293°K). At 20°C:

$$0.0224 \text{ m}^3 / \text{g - mol} \left(\frac{293}{273}\right) = 0.024 \text{ m}^3 / \text{g - mol of air}$$

Therefore,

$$G_m = Q_G \left(\frac{1 \text{ g - mol of air}}{0.024 \text{ m}^3}\right)$$

Given: $Q_G = 89.4 \text{ m}^3/\text{min}$

_____

$$G_m = 89.4 \text{ m}^3 / \min\left(\frac{1 \text{ g - mol}}{0.024 \text{ m}^3}\right)$$

$$= 3{,}538 \text{ g - mol of air / min}$$

5. **Calculate the minimum liquid flow rate, L_{min}.** The minimum liquid-to-gas ratio was calculated in step 3.

$$\left(\frac{L_m}{G_m}\right)_{min} = 38.4 \frac{\text{g - mol of water}}{\text{g - mol of air}}$$

Therefore,

$$\left(L_m\right)_{min} = G_m(38.4)$$

From step 4: G_m =   3,538 g-mol of air/min

$$\left(L_m\right)_{min} = \left(3{,}538 \frac{\text{g - mol of air}}{\min}\right)\left(38.4 \frac{\text{g - mol of water}}{\text{g - mol of air}}\right)$$

$$= 136{,}000 \frac{\text{g - mol of water}}{\min}$$

$$= 136.0 \frac{\text{kg - mol of water}}{\min}$$

Converting to mass units :

$$= \left(136.0 \frac{\text{kg - mol}}{\min}\right)\left(\frac{18 \text{ kg}}{\text{kg - mol}}\right)$$

$$= 2{,}448 \text{ kg/min}$$

6. **Figure 11-10 illustrates the graphical solution for this problem.** To obtain the actual operating line, multiply the minimum operating line by 1.5.

$$
\begin{aligned}
AC &= 1.5 \text{ AB} \\
AC &= 1.5\,(38.4) \\
&= 57.6
\end{aligned}
$$
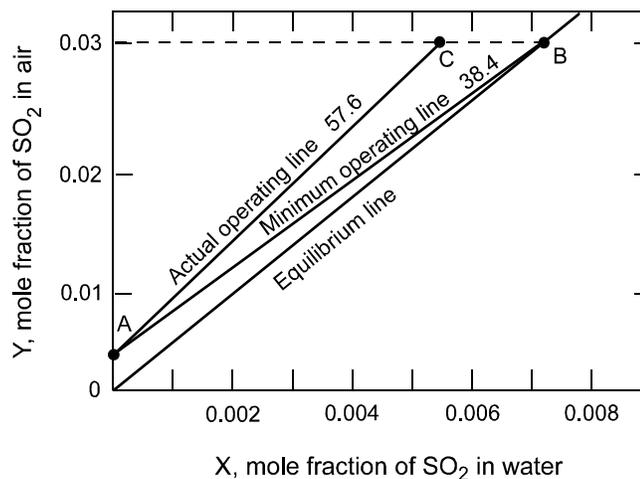
Figure 11-10.   Graphical solution to Example 11-2

To test your knowledge of the preceding section, answer the questions in Part 3 of the Review Exercise and work problem 1.

Sizing a Packed Tower

Packed Tower Diameter

The main parameter affecting the size of a packed column is the gas velocity at which liquid droplets become entrained in the exiting gas stream. Consider a packed column operating at set gas and liquid flow rates. By decreasing the diameter of the column, the gas flow rate (m/s or ft/sec) through the column will increase. If the gas flow rate through the column is gradually increased (by using smaller and smaller diameter columns), a point will be reached where the liquid flowing down over the packing begins to be held in the void spaces between the packing. This gas-to-liquid ratio is termed the **loading point**. The pressure drop of the column begins to increase and the degree of mixing between the phases decreases. A further increase in gas velocity will cause the liquid to completely fill the void spaces in the packing. The liquid forms a layer over the top of the packing and no more liquid can flow down through the tower. The pressure drop increases substantially, and mixing between the phases is minimal. This condition is referred to as flooding, and the gas velocity at which it occurs is the **flooding velocity**. Using an extremely large-diameter tower would eliminate this problem. However, as the diameter increases, the cost of the tower increases.

Normal practice is to size a packed column diameter to operate at a certain percent of the flooding velocity. A typical operating range for the gas velocity through the columns is 50 to 75% of the flooding velocity. It is assumed that, by operating in this range, the gas velocity will also be below the loading point.

A common and relatively simple procedure for estimating flooding velocity (thus, setting a minimum column diameter) is to use a generalized flooding and pressure drop correlation. One version of the flooding and pressure drop relationship for a packed tower is in the **Sherwood correlation**, shown in Figure 11-11 (Calvert et al. 1972). Figure 11-11, was developed from experimental data, knowing the physical properties of the gas and liquid streams and tower packing characteristics. In Figure 11-11, the terms and units must be used as presented since the relationships are based on empirical data. The "X" axis (or abscissa) is a function of the physical properties of the gas and liquid streams. The "Y" axis (ordinate), is also a function of the gas and liquid properties as well as the packing material utilized. The graph is used to predict what conditions will cause flooding to occur. Since flooding is an unacceptable operating condition, this sets a minimum tower diameter for a given set of gas/liquid conditions. Knowing minimum unacceptable diameter, a larger, *operating* diameter can be specified.
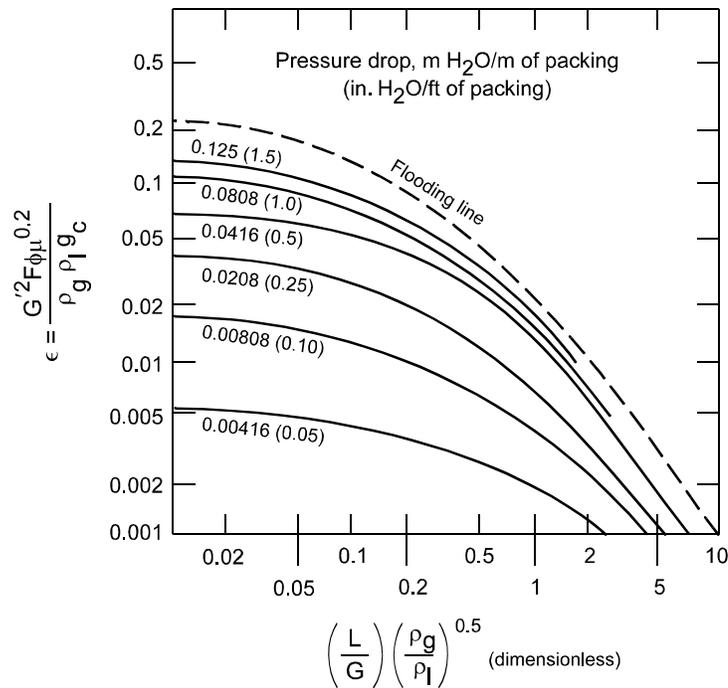
Figure 11-11.   Generalized flooding and pressure drop correlation
Source: Calvert et al. 1972.

_____

The procedure to determine the tower diameter is given below.

1. **Calculate the value of the abscissa**.

$$\text{Abscissa} = \left(\frac{L}{G}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{11-16}$$

Where: L and G = mass flow rates (any consistent set of units may be used as long as the term is dimensionless)

ρ_g = density of the gas stream

ρ_l = density of the absorbing liquid

2. **From the point calculated in Equation 11-16, proceed up the graph to the flooding line and read the ordinate, ε.**

3. **Rearrange the equation of the ordinate and solve for G'.**

$$G' = \left[\frac{(\epsilon)(\rho_g)(\rho_l)(g_c)}{F\phi\mu_l^{0.2}}\right]^{0.5} \tag{11-17}$$

Where: G' = mass flow rate of gas per unit cross-sectional area of column, g/s•m² (lb/sec•ft²)

ρ_g = density of the gas stream, kg/m³ (lb/ft³)

ρ_l = density of the absorbing liquid, kg/m³ (lb/ft³)

g_c = gravitational constant, 9.82 m/s² (32.2 ft/sec²)

F = packing factor given in Table 11-5 for different types of packing (Bhatia 1977)

ϕ = ratio of specific gravity of the scrubbing liquid to that of water

μ_l = viscosity of liquid

4. **Calculate G' at operating conditions.** G' at operating conditions is a fraction of G' at flooding conditions.

$$G'_{\text{operating}} = (f)(G'_{\text{flooding}}) \tag{11-18}$$

Where: f = the percent of flooding velocity, usually 50 to 75%

———

5. **Calculate the cross-sectional area of column A from Equation 11-19.**

$$A = \frac{G}{G'_{operating}} \tag{11-19}$$

6. **Calculate the diameter of the column from Equation 11-20.**

$$d_t = \left(\frac{4A}{\pi}\right)^{0.5} \tag{11-20}$$

$$= 1.13 \, A^{0.5}$$

Table 11-5. Packing data[1]					
Packing	**Size (in.)**	**Weight (lb/ft²)**	**Surface area, a (ft²/ft³ packing volume)**	**Void fraction (%)**	**Packing factor, F (ft²/ft³)**
Raschig rings (ceramic and porcelain)	1/2	52	114	65	580
	1	44	58	70	155
	1 1/2	42	36	72	95
	2	38	28	75	65
	3	34	19	77	37
Raschig rings (steel)	1/2 × 1/32	77	128	84	300
	1 × 1/32	40	63	92	115
	2 × 1/16	38	31	92	57
Berl saddles (ceramic and porcelain)	1/4	55	274	63	900
	1/2	54	155	64	240
	1	48	79	68	110
	2	38	32	75	45
Intalox saddles (ceramic)	1/4	54	300	75	725
	1/2	45	190	78	200
	1	44	78	77	98
	2	42	36	79	40
Intalox saddles (plastic)	1	6.00	63	91	30
	2	3.75	33	93	20
	3	3.25	27	94	15
Pall rings (plastic)	5/8	7.0	104	87	97
	1	5.5	63	90	52
	2	4.5	31	92	25

	Table 11-5.	*(continued)* Packing data[1]			
Pall rings (metal)	5/8 × 0.018 thick	38	104	93	73
		24	39	95	28
	1 1/2 × .03 thick				
Tellerettes	1	7.5	55	87	40
	2	3.9	38	93	20
	3	5.0	30	92	15

1. Note: Data for guide purposes only.
   Source: Bhatia 1977.

Example 11-3

This example illustrates the use of Figure 11-11 for computing the minimum allowable diameter for a packed tower. For the scrubber in Example 11-2, determine the column diameter if the operating liquid rate is 1.5 times the minimum. The gas velocity should be no greater than 75% of the flooding velocity, and the packing material is two-inch ceramic Intalox saddles.

Solution

1. **Determine the actual gas and liquid flow rates for the system**. For Example 11-2, the gas molar flow rate in the absorber, G_m, was 3,538 g-mol/min and the minimum liquid flow rate, L_{min}, was 2,448 kg/min. The actual liquid flow rate in the absorber should be 1.5 times the minimum flow rate:

$$
\begin{aligned}
L &= L_{min} \times 1.5 \\
&= (2{,}448 \text{ kg/min}) \, (1.5) \\
&= 3{,}672 \text{ kg/min}
\end{aligned}
$$

Assuming the molecular weight of the exhaust gas is 29 kg/mol, convert the gas molar flow rate (G_m) to mass flow rate (G).

$$
\begin{aligned}
G &= G_m \times (29 \text{ kg/kg-mol}) \\
G &= (3{,}538 \text{ g-mol/min})(29 \text{ kg/kg-mol}) \\
&= (3.538 \text{ kg-mol/min})(29 \text{ kg/kg-mol}) \\
&= 102.6 \text{ kg/min}
\end{aligned}
$$

2. **Using Equation 11-16, calculate the abscissa for Figure 11-11.**

$$
\text{Abscissa} = \left(\frac{L}{G}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.5}
$$

The densities of air and water at 30°C are:

$$\rho_g = 1.17 \text{ kg/m}^3$$
$$\rho_l = 1,000 \text{ kg/m}^3$$

$$\text{Abscissa} = \left(\frac{3,672}{102.6}\right)\left(\frac{1.17}{1,000}\right)^{0.5}$$

3. **Using Figure 11-12, with the abscissa of 1.22, move up to the flooding line and read the value of ε on the ordinate.**

$$\varepsilon = 0.019$$
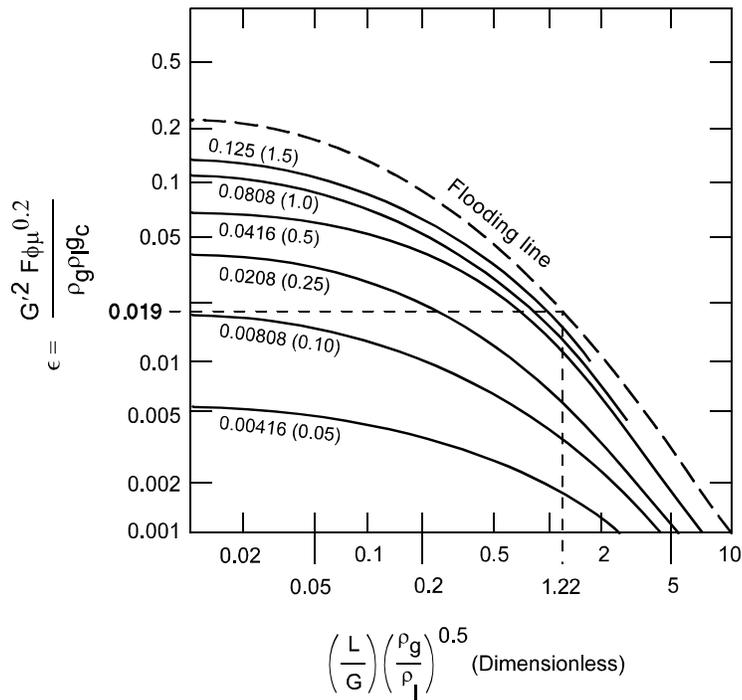
Figure 11-12.   Generalized flooding and pressure drop correlation for Example 11-3

_____

4. **Calculate the superficial flooding velocity, G'** using Equation
    11-17. The superficial flooding velocity is the flow rate per unit of cross-
    sectional area of the tower.

$$G' = \left[\frac{(\varepsilon)(\rho_g)(\rho_l)(g_c)}{F\phi\mu_l^{0.2}} \right]^{0.5}$$

Given:

ρ_g = 1.17 kg/m^3, density of air at 30°C
ρ_l = 1,000 kg/m^3, density of water at 30°C
g_c = 9.82 m/s^2, the gravitational constant
F = 40 ft^2/ft^3 (131 m^2/m^3), the packing factor for two-inch ceramic Intalox saddles (see Table 11-5)
ϕ = 1.0, the ratio of specific gravity of the scrubbing liquid(water) to that of water
μ_l = 0.0008 Pa•s, the viscosity of liquid

From step 3: ε = 0.019

$$G' = \left[\frac{(0.019)(1.17)(1000)(9.82)}{(1)(131)(0.0008)^{0.2}} \right]^{0.5}$$

$$= 2.63 \text{ kg} / \text{s} \bullet \text{m}^2 \text{ at flooding}$$

5. **Calculate the superficial gas velocity at operating conditions
    (G'$_{operating}$)** using Equation 11-18.

$$G'_{operating} = (f)(G'_{flooding})$$

Where: f = 75%

From step 4: $G'_{flooding}$ = 2.63 kg/s•m^2

$$G'_{operating} = (0.75)(2.63 \text{ kg/s} \bullet \text{m}^2)$$
$$= 1.97 \text{ kg/s} \bullet \text{m}^2$$

_____

6. **Calculate the cross-sectional area of the packed tower** using Equation 11-19.

$$A = \frac{G}{G'_{operating}}$$

From step 1:   G   = 102.6 kg/min
From step 5:   G'$_{operating}$ = 1.97 kg/s•m^2

$$A = \frac{(102.6 \text{ kg} / \text{min})(1 \text{ min} / 60 \text{ sec})}{1.97 \text{ kg} / \text{s} \bullet \text{m}^2}$$

$$= 0.87 \text{ m}^2$$

7. **Calculate the tower diameter** using Equation 11-20.

$$d_t = \left(\frac{4A}{\pi}\right)^{0.5}$$

Where: π =   3.14

From step 6:   A   =   0.87 m^2

$$d_t = \left[\frac{4(0.87)}{3.14}\right]^{0.5}$$

$$= 1.05 \text{ m}$$

$$\approx 1.1 \text{ m}$$

8. **Use Figure 11-11 to estimate the pressure drop across the absorber, Δp**, once the superficial gas velocity for operating conditions has been set. First, plug G'$_{operating}$ back into Equation 11-17 and rearrange the equation to get the ordinate, ε.

$$\varepsilon = \frac{G'^2 \phi F \mu_l^{0.2}}{\rho_g \rho_l g_c}$$

$$\varepsilon = \frac{\left(1.97 \text{ kg / s} \bullet \text{m}^2\right)^2 (1)\left(131 \text{ m}^2 / \text{m}^3\right)\left(0.0008 \text{ Pa} \bullet \text{s}\right)^{0.2}}{\left(1.17 \text{ kg / m}^3\right)\left(1,000 \text{ kg / m}^3\right)\left(9.82 \text{ m / s}^2\right)}$$

$$= 0.0106$$

The ordinate equals 0.0106 and the abscissa equals 1.22. Then from Figure 11-13, read Δp. The pressure drop equals 0.0416 m of water/m of packing.
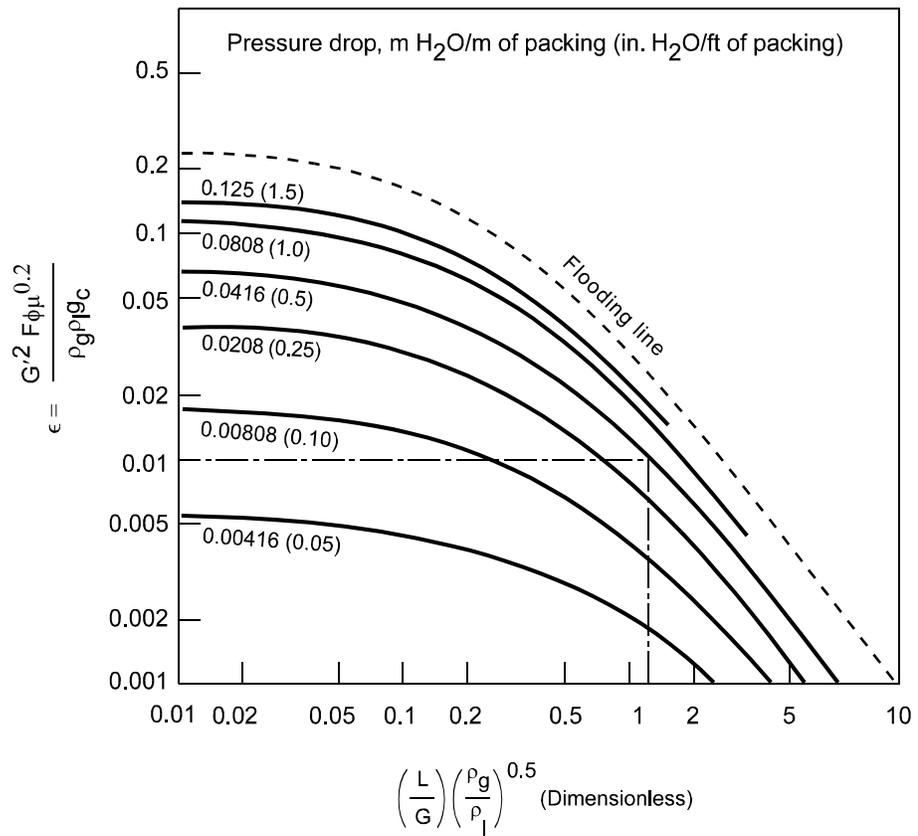
Figure 11-13.   Generalized flooding and pressure drop correlation for Example 11-3

Packed Tower Height

The height of a packed column refers to the depth of packing material needed to accomplish the required removal efficiency. The more difficult the separation, the larger the packing height required. For example, a much larger packing height would be required to remove SO_2 than to remove chlorine (Cl) from an exhaust stream using water as the absorbent because Cl is more soluble in water than SO_2 is. Determining the proper height of packing is important since it affects both the rate and efficiency of absorption.

A number of theoretical equations are used to predict the required packing height. These equations are based on diffusion principles. Depending on which phase is controlling the absorption process, either Equation 11-5 or 11-6 is used as the starting point to derive an equation to predict column height. A material balance is then set up over a small differential section (height) of the column.

The general form of the design equation for a *gas-phase controlled resistance* is given in Equation 11-21.

$$Z = \frac{G'}{K_{OG}aP} \int_{Y_2}^{Y_1} \frac{dY}{(1-Y)(Y-Y^*)} \qquad (11\text{-}21)$$

Where: Z = height of packing, m
G' = mass flow rate of gas per unit cross-sectional area of column, g/s•m^2
K_{OG}= overall mass-transfer coefficient based on the gas phase, g-mol/h•m^2•Pa
a = interfacial contact area, m^2
P = pressure of the system, kPa
Y_1 = inlet gas pollutant concentration
Y_2 = outlet gas pollutant concentration
Y^* = pollutant concentration in gas at equilibrium

In analyzing Equation 11-21, the term $G'/K_{OG}aP$ has the dimension of meters and is defined as the *height of a transfer unit*. The term inside the integral is dimensionless and represents the *number of transfer units* needed to make up the total packing height. Using the concept of transfer units, Equation 11-21 can be simplified to:

$$Z = HTU \times NTU \qquad (11\text{-}22)$$

Where: Z = height of packing, m
HTU = height of a transfer unit, m
NTU = number of transfer units

The concept of a transfer unit comes from the assumptions used in deriving Equation 11-21. These assumptions are: (1) that the absorption process is carried out in a series of contacts, or stages, and (2) that the streams leaving these stages are in equilibrium with each other. The stages can be visualized as the height of an individual transfer unit and the total tower height is equal to the number of transfer units times the height of each unit. Plate towers operate in this manner where they have discrete *contact* sections. Although a packed column operates as one continuous separation (differential contactor) process, in design terminology it is treated as discrete sections (transfer units) in order to perform a mass balance around a small subsection of the tower. The number and the height of a transfer unit are based on either the gas or the liquid phase. Equation 11-22 now becomes:

_____

$$Z = N_{OG}H_{OG} = N_{OL}H_{OL} \qquad (11\text{-}23)$$

Where: Z = height of packing, m
N_{OG} = number of transfer units based on an overall gas-film coefficient, K_{OG}
N_{OL} = number of transfer units based on an overall liquid-film coefficient, K_{OL}
H_{OG} = height of a transfer unit based on an overall gas-film coefficient, m
H_{OL} = height of a transfer unit based on an overall liquid-film coefficient, m

The number of transfer units, NTU, can be obtained experimentally or calculated from a variety of methods. For the case where the solute concentration is very low and the equilibrium line is straight, Equation 11-24 can be used to determine the number of transfer units (N_{OG}) based on the gas-phase resistance. Equation 11-24 can be derived from the integral portion of Equation 11-21.

$$N_{OG} = \frac{\ln\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{1 - \dfrac{mG_m}{L_m}} \qquad (11\text{-}24)$$

Where: N_{OG} = number of transfer units based on an overall gas-film coefficient, K_{OG}
Y_1 = mole fraction of solute in entering gas
Y_2 = mole fraction of solute in exiting gas
m = slope of equilibrium line
X_2 = mole fraction of solute entering the column
G_m = molar flow rate of gas, kg-mol/h
L_m = molar flow rate of liquid, kg-mol/h

Equation 11-24 may be solved directly or graphically by using the Colburn diagram, which is presented in Figure 11-13. The Colburn diagram is a plot of the N_{OG} versus $\ln[Y_1 - mX_2/Y_2 - mX_2]$ at various values of (mG_m/L_m). The term (mG_m/L_m) is referred to as the *absorption factor*. In using Figure 11-14, first compute the value of $[Y_1 - mX_2/Y_2 - mX_2]$; next read up the graph to the line corresponding to (mG_m/L_m), and then read across to obtain the N_{OG}.
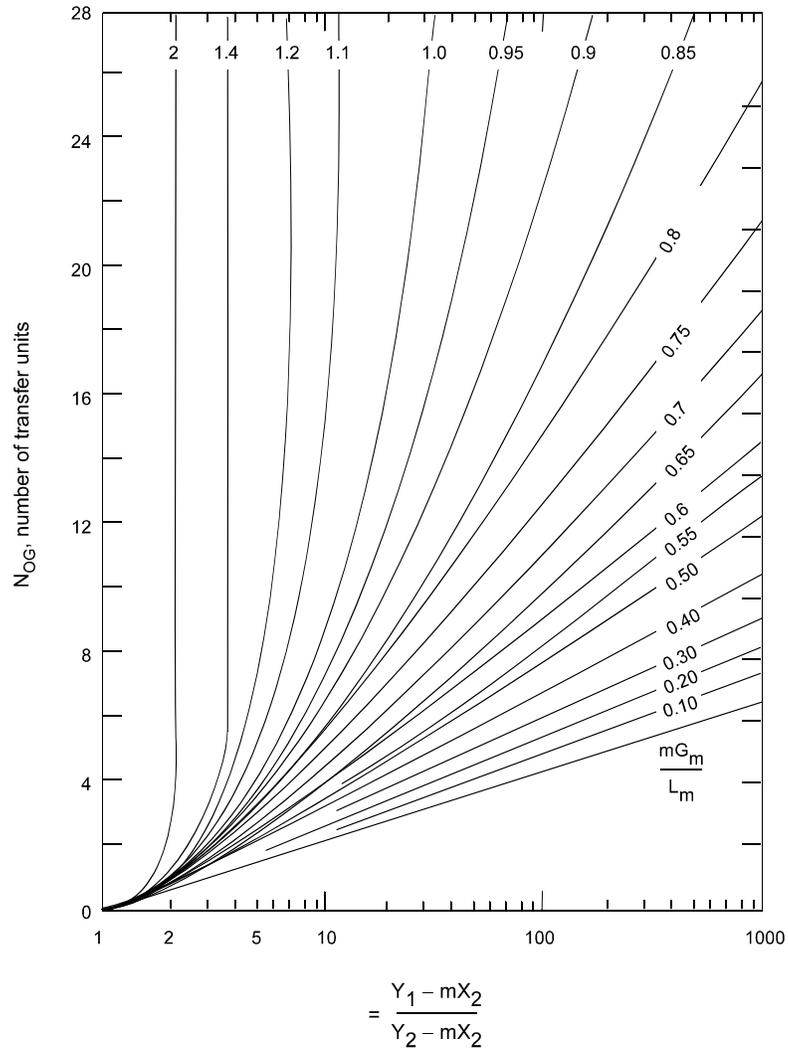
Figure 11-14.   Colburn diagram
Source: Perry 1973.

Equation 11-24 can be further simplified for situations where a chemical reaction occurs or if the solute is extremely soluble. In these cases, the solute exhibits almost no partial pressure; therefore, the slope of the equilibrium line approaches zero (m $\rightarrow$ 0). For either of these cases, Equation 11-24 reduces to Equation 11-25.

$$N_{OG} = \ln \frac{Y_1}{Y_2}$$ (11-25)

The number of transfer units depends only on the inlet and outlet concentration of the solute. For example, if the conditions of Equation 11-25 are met, achieving 90% removal of any pollutant requires 2.3 transfer units. Equation 11-25 applies only when the equilibrium line is straight and the slope approaches zero (for very soluble or reactive gases).

_____

Values for the height of a transfer unit used in designing absorption systems are usually obtained from experimental data. To ensure greatest accuracy, vendors of absorption equipment normally perform pilot plant studies to determine the HTU. For common absorption systems, such as NH_3 and water, manufacturers have developed graphs for estimating HTU. These graphs do not provide the accuracy of pilot plant data, but are less expensive and easier to use. Figure 11-15 gives a typical example of these graphs for an ammonia and water system. In this figure, the superficial liquid flow rate is plotted versus the H_{OG} with the superficial gas rate as a parameter. For a given liquid flow rate, the height of a transfer unit for the 1-inch Tellerettes is less than that for the 1-1/2 inch Raschig rings. Therefore, a system would need *less* Tellerette packing to accomplish the same removal. For this example the Tellerettes would be more efficient. It is also common to plot gas rate versus the H_{OG} and have the liquid rate as a parameter. Additional information on other gas-liquid systems can be found in *Chemical Engineers' Handbook* (Perry 1973). In applying these data, process conditions must be similar to conditions at which the HTU was measured.
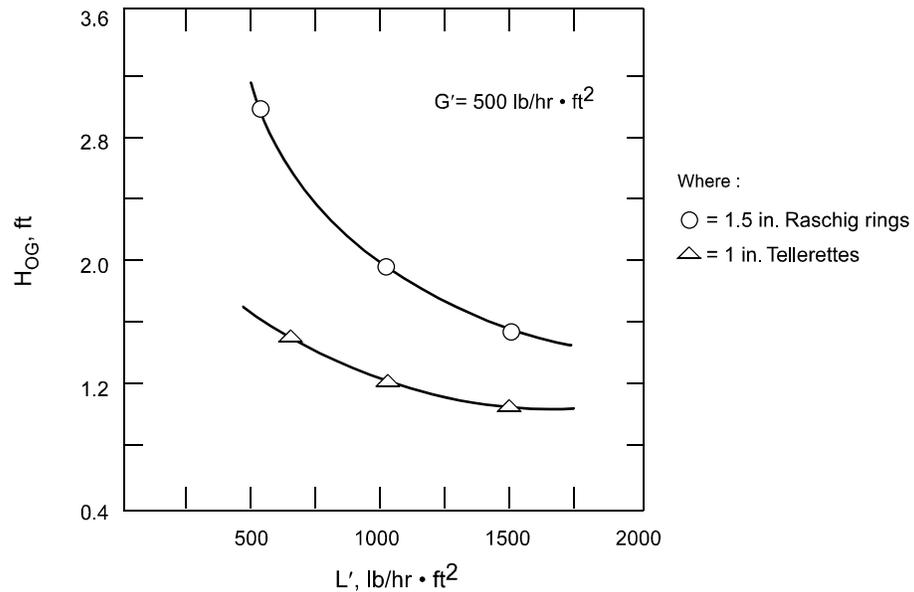
Figure 11-15.   Column packing comparison for ammonia
and water system

When no experimental data are available, or if only a preliminary estimate of absorber efficiency is needed, generalized correlations are available to predict the height of a transfer unit. The correlations for predicting the H_{OG} or the H_{OL} are empirical in nature and are a function of:

1. Type of packing
2. Liquid and gas flow rates
3. Concentration and solubility of the pollutant
4. Liquid properties
5. System temperature

These correlations can be found in engineering texts such as *Chemical Engineers' Handbook* (Perry 1973), *Wet Scrubber System Study, Volume I* (Calvert et al. 1972), or *Mass Transfer Operations* (Treybal 1968). For most applications, the height of a transfer unit ranges between 0.3 and 1.2 m (1 to 4 ft) (Calvert 1977). As a rough estimate, 0.6 m (2.0 ft) can be used.

Example 11-4

From pilot plant studies of the absorption system in Example 11-2 it was determined that the H_{OG} for the SO_2-water system is 0.829 m (2.72 ft). Calculate the total height of packing required to achieve 90% removal. The following data were taken from the previous examples.

m, Henry's law constant for the equilibrium diagram for SO_2 and water system (see Example 11-1).	$42.7 \dfrac{\text{kg - mol of water}}{\text{kg - mol of air}}$
G_m, molar flow rate of gas	3.5 kg-mol/min
L_m, molar flow rate of liquid	3,672 kg/min $\times$ kg-mol/18 kg = 204 kg-mol/min
X_2, mole fraction of solute in entering liquid	0 (no recycle liquid)
Y_1, mole fraction of solute in entering gas	0.03
Y_2, mole fraction of solute in existing gas	0.003

Solution

1. **Calculate the number of transfer units, N_{OG},** using Equation 11-24.

$$N_{OG} = \frac{\ln\left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \frac{mG_m}{L_m}\right) + \frac{mG_m}{L_m}\right]}{1 - \frac{mG_m}{L_m}}$$

$$N_{OG} = \frac{\ln\left[\left(\frac{0.03}{0.003}\right)\left(1 - \frac{(42.7)(3.5)}{204}\right) + \frac{(42.7)(3.5)}{204}\right]}{1 - \frac{(42.7)(3.5)}{204}}$$

$$= 5.04$$

2. **Calculate the total packing height, Z,** using Equation 11-23.

$$Z = H_{OG} \times N_{OG}$$

Given: H_{OG} = 0.829 m, height of a transfer unit

From step 1: N_{OG} = 5.04 m

$$
\begin{aligned}
Z &= (0.829 \text{ m})(5.04) \\
&= 4.18 \text{ m of packing height}
\end{aligned}
$$

To test your knowledge of the preceding section, answer the questions in Part 4 of the Review Exercise and work problem 2.

Sizing a Plate Tower

Another scrubber used extensively for gas absorption is a plate tower. Here, absorption occurs on each plate, or stage. These are commonly referred to as discrete stages, or steps. The following discussion presents a simplified method for sizing or reviewing the design plans of a plate tower. The method for determining the liquid flow rate in the plate tower is the same as previously discussed. Methods for estimating the diameter of a plate tower and the theoretical number of plates follow.

Plate Tower Diameter

The minimum diameter of a single-pass plate tower is determined by using the gas velocity through the tower. If the gas velocity is too fast, liquid droplets are entrained,

causing a condition known as priming. **Priming** occurs when the gas velocity through the tower is so fast that it causes liquid on one tray to foam and then rise to the tray above. Priming reduces absorber efficiency by inhibiting gas and liquid contact. For the purpose of determining tower diameter, priming in a plate tower is analogous to the flooding point in a packed tower. It determines the **minimum acceptable diameter**. The **actual diameter** should be larger.

The smallest allowable diameter for a plate tower is expressed in Equation 11-26.

$$d_t = \psi \left(Q_G \sqrt{\rho_g} \right)^{0.5} \tag{11-26}$$

Where: Q_G = volumetric gas flow, m^3/h
    ψ = empirical correlation, $m^{0.25}h^{0.5}/kg^{0.25}$
    ρ_g = gas density, kg/m^3

The term ψ is an empirical correlation and is a function of both the tray spacing and the densities of the gas and liquid streams. Values for ψ in Table 11-6 are for a tray spacing of 61 cm (24 in.) and a liquid specific gravity of 1.05 (Calvert et al. 1972). If the specific gravity of a liquid varies significantly from 1.05, the values for ψ in Table 11-6 *cannot* be used.

Table 11-6. Empirical constants for Equation 11-26		
Tray	**Metric Ψ^a**	**English Ψ^b**
Bubble cap	0.0162	0.1386
Sieve	0.0140	0.1198
Valve	0.0125	0.1069

a. Metric Ψ is expressed in $m^{0.25} h^{0.5}/kg^{0.25}$, for use with Q_G expressed in m^3/h, and ρ_g expressed in kg/m^3.

b. English Ψ is expressed in $ft^{0.25} min^{0.5}/lb^{0.25}$, for use with Q_G in cfm, and ρ_g expressed in lb/ft^3.

Source: Calvert et al. 1972.

Depending on operating conditions, trays are spaced with a minimum distance between plates to allow the gas and liquid phases to separate before reaching the plate above. Trays should be spaced to allow for easy maintenance and cleaning. Trays are normally spaced 45 to 70 cm (18 to 28 in.) apart. In using Table 11-6 for a tray spacing different from 61 cm, a correction factor must be used. Figure 11-16 is used to determine the correction factor, which is multiplied by the estimated diameter. Example 11-5 illustrates how to estimate the minimum diameter of a plate tower.
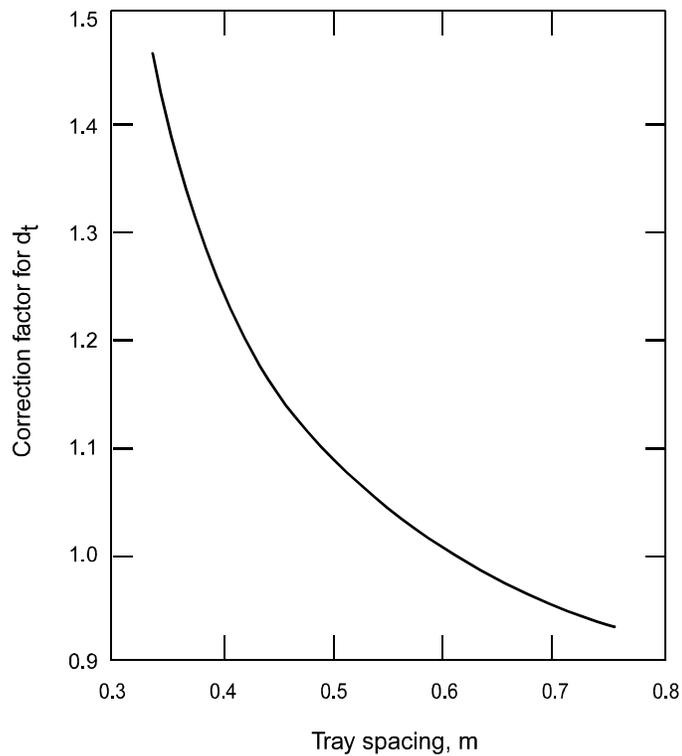
Figure 11-16.   Tray spacing correction factor
Source: Calvert et al. 1972.

Example 11-5

For the conditions described in Example 11-2, determine the minimum acceptable diameter if the scrubber is a bubble-cap tray tower. The trays are spaced 0.53 m (21 in.) apart.

Solution

To determine the minimum acceptable diameter of the plate tower, we will use Equation 11-26:

$$d_t = \psi \left(Q_G \sqrt{\rho_g} \right)^{0.5}$$

From Example 11-2, the following information is obtained:

Q_G, gas flow rate = 84.9 m³/min
ρ_g, gas density   = 1.17 kg/m³

___

1. **Convert the gas flow rate, Q_G, to units of m³/h.**

$$Q_G = (84.9 \text{ m}^3/\text{min}) (60 \text{ min/hr})$$
$$= 5{,}094 \text{ m}^3/\text{h}$$

2. **Determine the empirical constant, ψ.** From Table 11-6, the value for ψ is $0.0162 \text{ m}^{0.25} \text{ h}^{0.5}/\text{kg}^{0.25}$.

3. **Calculate the minimum diameter, d_t, of the plate tower** using Equation 11-26.

$$d_t = \psi \left(Q_G \sqrt{\rho_g} \right)^{0.5}$$

Given: $\qquad \rho_g = 1.17 \text{ kg/m}^3$

From step 1: $\qquad Q_G = 5{,}094 \text{ m}^3/\text{h}$
From step 2: $\qquad \psi = 0.0162 \text{ m}^{0.25} \text{ h}^{0.5}/\text{kg}^{0.25}$

$$d_t = (0.0162) \left[5{,}094 \left(\sqrt{1.17} \right) \right]^{0.5}$$
$$= 1.2 \text{ m}$$

4. **Correct the diameter using Figure 11-16.** The tray spacing for each tray is 0.53 m but the values in Table 11-6 are for a tray spacing of 0.61 m. Read a correction factor of 1.05.
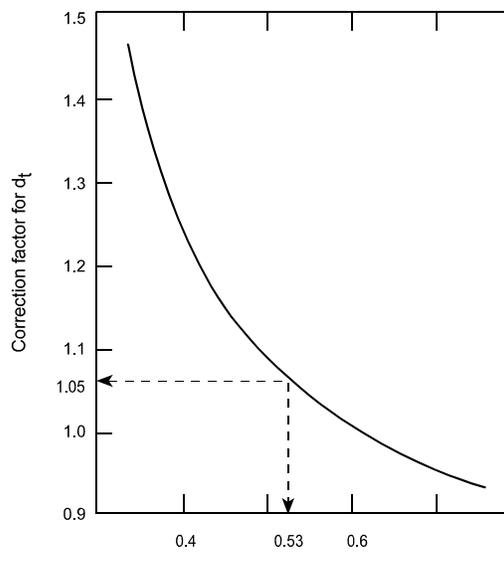
Figure 11-17.   Tray spacing correction factor for Example 11-5

5. **Adjust the minimum plate tower diameter value by using the correction factor.**

$$\text{Adjusted } d_t = d_t \left(\text{from step 3}\right) \times \text{correction factor}$$
$$d_t = 1.2 \text{ m } (1.05)$$
$$= 1.26 \text{ m}$$

Note: The value of 1.26 m is the minimum estimated tower diameter based on priming conditions. In practice, a larger diameter based on economic conditions is usually chosen.

Number of Theoretical Plates

Several methods are used to determine the number of ideal plates, or trays, required for a given removal efficiency. These methods, however, can become quite complicated. One method used is a graphical technique. The number of ideal plates is obtained by drawing "steps" on an operating diagram. This procedure is illustrated in Figure 11-18. This method can be rather time consuming, and inaccuracies can result at both ends of the graph.

Note: Lines AB-BC are one theoretical plate.
        Need a total of 2.3 plates.
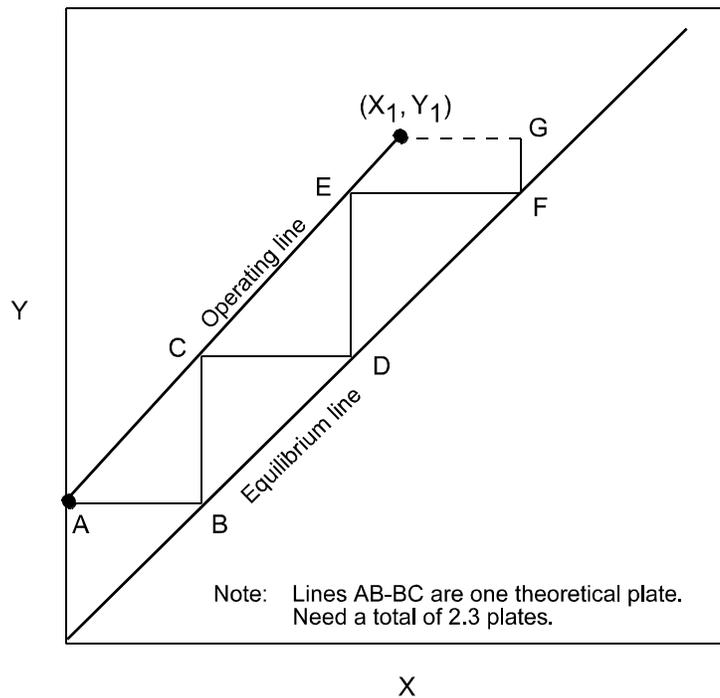
Figure 11-18.   Graphic determination of the number of theoretical plates

Equation 11-27 is a simplified method used to estimate the number of plates. This equation can only be used if both the equilibrium and operating lines for the system are straight. This is a valid assumption for most air pollution control systems. This equation, taken from Sherwood and Pigford (1952), is derived in the same manner as Equation 11-24 for computing the N_{OG} of a packed tower. The difference is that Equation 11-27 is based on a stepwise solution instead of a continuous contactor, as is the packed tower. (Note: This derivation is referred to as the **height equivalent to a theoretical plate**, or **HETP** instead of HTU.)

$$N_p = \frac{\ln\left[\left(\frac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \frac{mG_m}{L_m}\right) + \frac{mG_m}{L_m}\right]}{\ln\left(\frac{L_m}{mG_m}\right)}$$ (11-27)

This equation is used to predict the number of *theoretical* plates required to achieve a given removal efficiency. The operating conditions for a theoretical plate assume that the gas and liquid streams leaving the plate are in equilibrium with each other. This ideal condition is never achieved in practice. A larger number of **actual trays** are required to compensate for this decreased tray efficiency.

Three types of efficiencies are used to describe absorption efficiency for a plate tower:

1. An *overall efficiency*, which is concerned with the entire column

2. *Murphree efficiency*, which is applicable with a single plate

3. *Local efficiency*, which pertains to a specific location on a plate

A number of methods are available to predict these plate efficiencies. These methods are complex, and values predicted by two different methods for a given system can vary by as much as 80% (Zenz 1972).

The simplest of tray efficiency concepts, the overall efficiency, is the ratio of the number of theoretical plates to the number of actual plates. Since overall tray efficiency is an over-simplification of the process, reliable values are difficult to obtain. For a rough estimate, overall tray efficiencies for absorbers operating with low-viscosity liquid normally fall in a 65 to 80% range (Zenz 1972).

Example 11-6

Calculate the number of theoretical plates required for the scrubber in Example 11-5 using the same conditions as those in Example 11-4. Estimate the total height of the column if the trays are spaced at 0.53-m intervals, and assume an overall tray efficiency of 70%.

_____

Solution

1. **Estimate the number of theoretical plates** by using Equation 11-27.

$$N_p = \frac{\ln\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{\ln\left(\dfrac{L_m}{mG_m}\right)}$$

From Example 11-5 and the previous examples, the following data are obtained:

m	=	42.7, Henry's law equilibrium constant
Y_1, (inlet gas)	=	0.03 mole fraction
Y_2, (outlet gas)	=	0.003 mole fraction
X_2, (inlet liquid)	=	0.0 mole fraction
L_m	=	204 kg-mol/min, the molar flow rate of liquid
G_m	=	3.5 kg-mol/min, the molar flow rate of gas

$$N_p = \frac{\ln\left[\left(\dfrac{0.03 - 0}{0.003 - 0}\right)\left(1 - \dfrac{(42.7)(3.5)}{204}\right) + \dfrac{(42.7)(3.5)}{204}\right]}{\ln\left(\dfrac{204}{(42.7)(3.5)}\right)}$$

= 3.94 theoretical plates

2. **Estimate the actual number of plates assuming that the overall efficiency of each plate is 70%.**

$$\text{Actual plates} = \frac{\text{estimated plates}}{70\%}$$

$$\text{Actual plates} = \frac{3.94}{0.70}$$

= 5.6 or 6 plates (since you can't have a fraction of a plate)

3. **Estimate the height of the tower, Z,** by using the following equation:

$$Z = (N_p \times \text{tray spacing}) + \text{top height of tower}$$

The top height of the tower is the distance that allows the gas-vapor mixture to separate. This distance is usually the same distance as the tray spacing.

$$
\begin{aligned}
Z &= (6 \text{ plates}) (0.53 \text{ m}) + 0.53 \text{ m} \\
&= 3.18 + 0.53 \\
&= 3.71 \text{ m}
\end{aligned}
$$

Note: This height is approximately the same as that predicted for the packed tower in Example 11-4. This seems logical since both packed and plate towers are efficient gas-absorption devices. However, due to the many assumptions, no concrete generalization can be made.

Summary

For gas absorption, the two devices most often used are the packed tower and the plate tower. Both of these devices, if designed and operated properly, can achieve high collection efficiencies for a wide variety of gases. Other scrubbing systems can be used for absorption, but are limited to cases where the gases are highly soluble. For example, spray towers, venturis, and cyclonic scrubbers are designed assuming the performance is equivalent to one single equilibrium stage (i.e., $N_{OG} = 1$) (Perry 1973).

The equations and procedures used in designing packed and plate towers are very similar. Both are based on solubility, the mass-transfer model, and the geometry of the tower. The main difference is that the equations for a plate tower are based on a stepwise process, whereas those for a packed tower are based on a continuous-contacting process. Care must be taken when applying any of the equations presented in this lesson (or in other texts). Some of the equations are empirical and are applicable only under a similar set of conditions. Used correctly, these procedures can be a useful tool in checking absorber designs or in determining the effect of a process change on absorber operation.

When checking the design plans for the permit process, the agency engineer should check its files or another agency's files for similar applications for absorber installations. A review of these data will help determine if the absorber design specifications submitted by the industrial source's officials are adequate to achieve pollutant removal efficiency for compliance with the regulations. The agency engineer should require the source owner/operator to conduct stack tests (once the source is operating) to determine if the source is in compliance with local, state, and federal regulations. The agency engineer should also require that the source owner/operator submit an operation and maintenance schedule that will help keep the scrubber system on line.

To test your knowledge of the preceding section, answer the questions in Part 5 of the Review Exercise and work problem 3.

Review Exercise

Questions

Part 1

1. Of the wet collectors listed below, which is/are the best device(s) for removing gaseous pollutants from process exhaust streams?

    a. Packed tower
    b. Plate tower
    c. Venturi scrubber
    d. Centrifugal scrubber
    e. a and b

2. In the absorption process, the *solute* is the:

    a. Inert portion of the gas stream
    b. Area where the gas phase and liquid phase come into contact with each other
    c. Gaseous pollutant that is absorbed
    d. Capability of a gas to be dissolved in a liquid

3. A very important factor affecting the amount of a pollutant that can be absorbed is its

    _____.

4. In an absorber, as the temperature of the system increases, the amount of pollutant that can be absorbed _____.

    a. Increases
    b. Decreases

5. A plot of the mole fraction of the solute in the liquid phase versus the mole fraction of the solute in the gas phase is called:

    a. The partial pressure
    b. An equilibrium diagram
    c. A concentration gradient

6. What is one form of the equation for Henry's law?

    a. $x = Hp$
    b. $H = xp$
    c. $H = x/y$
    d. $y = H'x$

7. In describing the solubility of various gases in water, the _____ Henry's law constant is, the more soluble the gas is.

    a. Smaller
    b. Larger

Part 2

8. In the double-resistance, or two-film theory, a _____ zone exists that includes a gas and liquid phase on either side of the interface.

   a. Soluble
   b. Mass-transfer
   c. Droplet

9. True or False? The two-film theory implies that **all** resistance to movement occurs when the molecule (gaseous pollutant) is diffusing through the gas and liquid films.

10. In absorption equations, the concentration of a gaseous pollutant is usually expressed by its:

    a. Diffusion rate
    b. Total pressure
    c. Partial pressure

11. In calculating the rate of mass transfer of pollutant A, N_A, using the equation

    $N_A = K_{OG}\left(p_{AG} - p_A^*\right)$, the term K_{OG} is the:

    a. Equilibrium concentration of pollutant A
    b. Mass-transfer coefficient for the gas film
    c. Mass-transfer coefficient for the liquid film
    d. Overall mass-transfer coefficient based on the gas phase

12. True or False? Overall mass-transfer coefficients are only valid when a plot of the equilibrium data yields an equilibrium line that is straight.

Part 3

13. In absorption calculations, a(an) _____ equates the gas and liquid concentrations coming into the absorber with the gas and liquid concentrations going out of the absorber.

    a. Material balance
    b. Energy balance
    c. Transfer unit

14. In air pollution calculations, the mass of the pollutant is usually very _____ compared to the mass of exhaust gas being treated and the mass of the liquid used in the absorber.

    a. Small
    b. Large

15. In the graph below, the line AB is the:

    a. Equilibrium line
    b. Actual operating line
    c. Minimum operating line
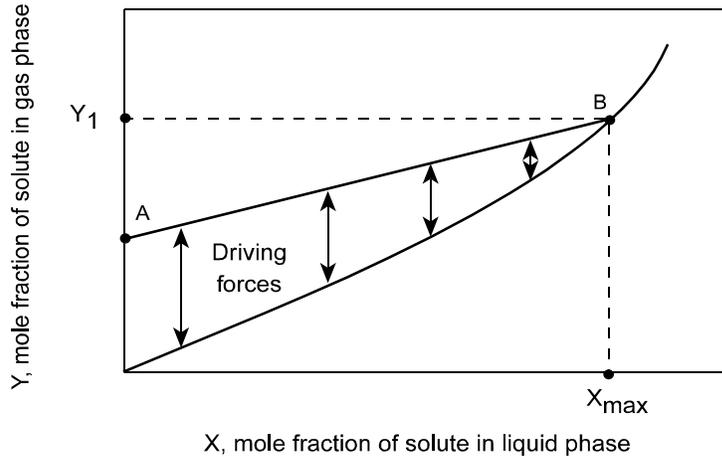
16. The slope of the actual operating line is:

    a. Minimum liquid-to-gas ratio
    b. G_m/L_m (actual)
    c. L_m/G_m (actual)

17. True or False? In the following figure, point B represents absorber conditions where the liquid leaving the absorber is saturated with the pollutant and can no longer absorb any additional pollutant, unless more liquid is added.
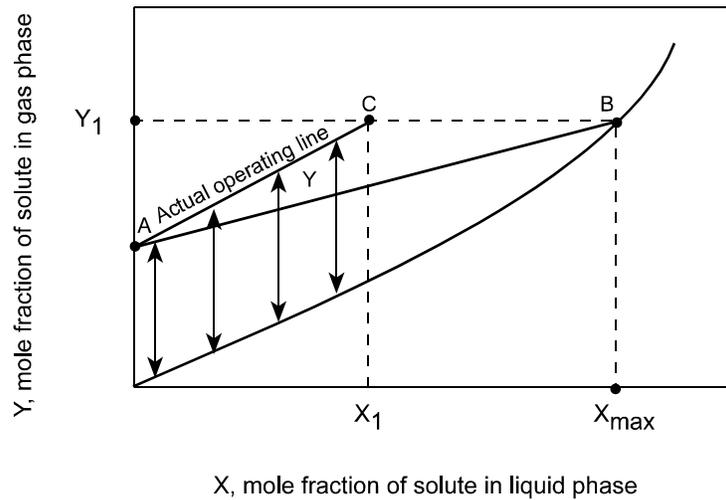
Part 4

18. In designing a packed tower, the normal practice is to make the tower diameter so that the unit will operate at _____ of the flooding velocity rate.

    a. 50 to 75%
    b. 100%
    c. 150%

19. True or False? The Sherwood correlation can be used to calculate the tower diameter of a packed tower, if the minimum liquid rate, L_m, and the gas flow rate, G, through the absorber are known.

20. In estimating packing height in a packed tower, the packing sections are broken up into discrete sections called:

    a. Transfer units
    b. Gas-film coefficients
    c. Liquid-film coefficients

21. The packing height, Z, can be estimated from the following equation:

$$Z = HTU \times NTU$$

    What are the terms HTU and NTU?

    HTU: _____

    NTU: _____

22. True or False? The Colburn diagram can be used to estimate the number of transfer units based on an overall gas-film coefficient, N_{OG}, if the absorption factor (mG_m/L_m), the inlet and outlet pollutant concentrations, and the liquid recycle concentrations are known.

23. The height of a transfer unit is a function of:

    a. Type of packing
    b. Liquid and gas flow rates
    c. Pollutant concentration and solubility
    d. Liquid properties and system temperature
    e. All of the above

24. For most packed tower applications, the height of a transfer unit can be estimated to be:

    a. 3 to 4.6 m (10 to 15 ft)
    b. 0.3 to 1.2 m (1 to 4 ft)
    c. 1.82 to 3 m (6 to 10 ft)

Part 5

25. In a plate tower, if the gas velocity through the tower is too fast, liquid droplets become entrained in the gas stream, causing a condition called:

    a. Pumping
    b. Streaking
    c. Priming

26. True or False? For the purpose of determining a plate-tower diameter, priming in a plate tower is the same as the flooding point in a packed tower.

27. In a plate tower, the following equation

$$N_p = \frac{\ln\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{\ln\left(\dfrac{L_m}{mG_m}\right)}$$

    is used to calculate the:

    a. Number of transfer units based on an overall gas-film coefficient
    b. Number of transfer units based on Henry's law constant
    c. Number of theoretical plates

28. In plate towers, the efficiency of each plate, or tray, is usually _____.

    a. 20 to 30%
    b. 65 to 80%
    c. 90 to 100%

_____

Problem 1

A medical waste incinerator utilizes a packed scrubber to remove HCl and other soluble gases. Given the operating conditions below, estimate the scrubbing liquid volumetric flow rate, Q_L, (essentially water with some caustic added to control pH) to achieve the required removal efficiency.

Q_G,	gas flow	15,000 acfm at 500°F
Y_1,	concentration of HCI in inlet gas	1,000 ppm or 47 lb/hr
Y_2,	concentration of HCI in outlet gas	30 ppm or 1.4 lb/hr
X_2,	concentration of HCI in inlet liquid	0
m,	Henry's Law equilibrium constant	1.1
	actual flow rate	1.5 times minimum
ρ_l,	density of water	8.35 lb/gal
R,	ideal gas constant at 70°F	380 scf/lb-mole
	molecular weight of water	18 lb/mole
	molecular weight of HCI	36 lb/mole
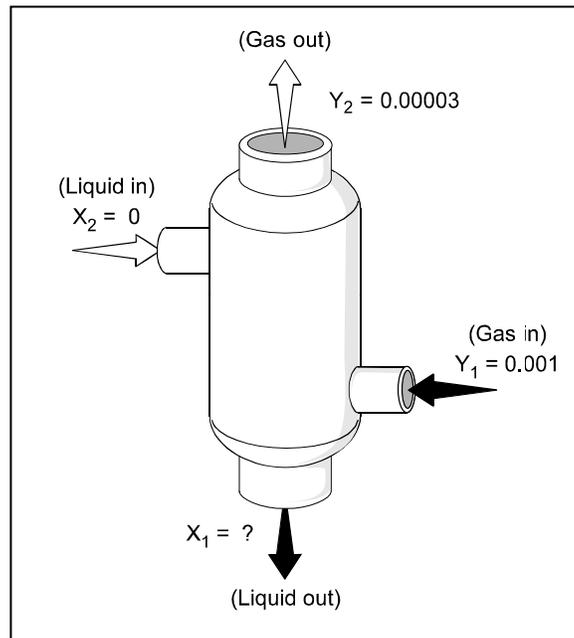
Problem 1: Student Worksheet
(This space is provided for you to work problem 1)

Problem 1: Student Worksheet (cont'd)

(This space is provided for you to work problem 1)

_____

Problem 2

A sewage treatment plant utilizes a countercurrent flow, packed bed scrubber to control odor emissions. The scrubbing liquid uses potassium permanganate solution in water and the packing material is 1 inch Berl ceramic saddles. Because of development in the area, the treatment plant needs to increase capacity by 25%. Given the data below, can the present tower accommodate the added flows?

		Existing	**Proposed**
Q_G,	volumetric flow rate of gas	10,000 acfm	12,500 acfm
Q_L,	volumetric flow rate of liquid	100 gal/min	125 gal/min
T,	temperature of gas	70°F	70°F
μ_l,	viscosity of liquid	0.018 centipoise	0.018 centipoise
ρ_l,	density of liquid	64 lb/ft³	64 lb/ft³
ρ_g,	density of gas	0.075 lb/ft³	0.075 lb/ft³
ϕ,	ratio of specific gravity of scrubbing liquid to that of water	1.01	1.01
F,	packing factor	45 ft³	45 ft³
	tower diameter	4 ft	4 ft

Constants and assumptions:

R, ideal gas constant (at 70°F)	380 scf/lb-mole
g_c, gravitational constant	32.2 lb/sec²
molecular weight of flue gas (assume it is essentially air)	29 lb/lb-mole
1 gal	0.134 ft³

Problem 2: Student Worksheet
(This space is provided for you to work problem 2)

Problem 2: Student Worksheet (cont'd)

(This space is provided for you to work problem 2)

Problem 2: Student Worksheet (cont'd)
(This space is provided for you to work problem 2)

_____

Problem 3

Calculate the number of theoretical plates required by a scrubber given the data below. Also, estimate the total height of a column if tray spacing is 2 ft and the overall tray efficiency is 70%. Assume that the top spacing is also 2 ft.

Q_G,	volumetric gas flow rate	15,000 acfm at 500°F
Y_1,	concentration of HCI in entering gas	1,000 ppm or 0.01 mole fraction
Y_2,	concentration of HCI in exiting gas	30 ppm or 0.00003 mole fraction
m,	Henry's law equilibrium constant	1.1
X_2,	concentration of HCI in inlet liquid	0
Q_L,	volumetric liquid flow rate	123 gal/min
ρ_l,	density of water	8.35 lb/gal
R,	the ideal gas constant (at 70°F)	380 scf/lb-mole
	molecular weight of water	18 lb/mole

Problem 3: Student Worksheet
(This space is provided for you to work problem 3)

Problem 3: Student Worksheet (cont'd)

(This space is provided for you to work problem 3)

Review Exercise Answers
Answers to Questions

Part 1

1. **e. a and b**
   Packed towers and plate towers are better than venturi scrubbers and centrifugal scrubbers for removing gaseous pollutants from process exhaust streams.

2. **c. Gaseous pollutant that is absorbed**
   In the absorption process, the *solute* is the gaseous pollutant that is absorbed.

3. **Solubility**
   A very important factor affecting the amount of a pollutant that can be absorbed is its solubility.

4. **b. Decreases**
   In an absorber, as the temperature of the system increases, the amount of pollutant that can be absorbed decreases.

5. **b. An equilibrium diagram**
   A plot of the mole fraction of the solute in the liquid phase versus the mole fraction of the solute in the gas phase is called an equilibrium diagram.

6. **d. y = H'x**
   One form of the equation for Henry's law is:

$$y = H'x$$

7. **a. Smaller**
   In describing the solubility of various gases in water, the smaller Henry's law constant is, the more soluble the gas is.

Part 2

8. **b. Mass-transfer**
   In the double-resistance, or two-film theory, a mass transfer zone exists that includes a gas and liquid phase on either side of the interface.

9. **True**
   The two-film theory implies that all resistance to movement occurs when the molecule (gaseous pollutant) is diffusing through the gas and liquid films.

10. **c. Partial pressure**
    In absorption equations, the concentration of a gaseous pollutant is usually expressed by its partial pressure.

11. **d. Overall mass-transfer coefficient based on the gas phase**
    In calculating the rate of mass transfer of pollutant A (i.e. N_A) using the equation
    $N_A = K_{OG}\left(p_{AG} - p_A^*\right)$, the term K_{OG} is the overall mass-transfer coefficient based on the gas phase.

12. **True**
    Overall mass-transfer coefficients are only valid when a plot of the equilibrium data yields an equilibrium line that is straight.

Part 3

13. **a. Material balance**
    In absorption calculations, a material balance equates the gas and liquid concentrations coming into the absorber with the gas and liquid concentrations going out of the absorber.

14. **a. Small**
    In air pollution calculations, the mass of the pollutant is usually very small compared to the mass of exhaust gas being treated and the mass of the liquid used in the absorber.

15. **c. Minimum operating line**
    In the graph below, the line AB is the minimum operating line.
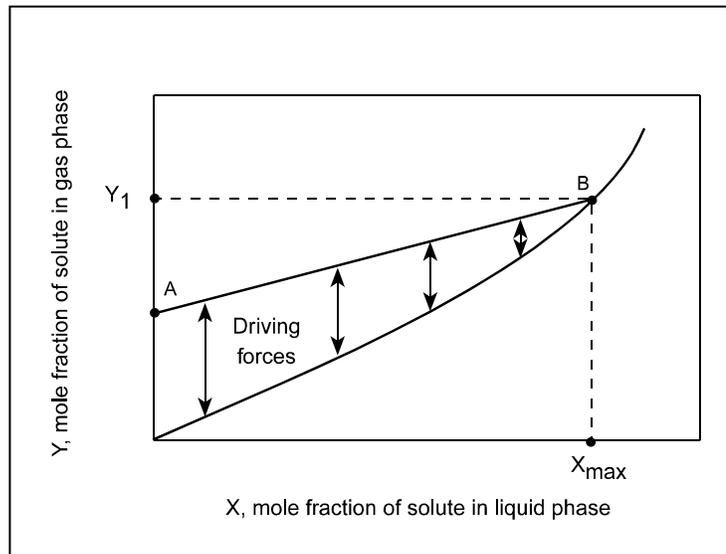
16. **c. L�m/Gₘ (actual)**
    The slope of the actual operating line is L_m/G_m (actual).

17. **True**
    In the following figure, point B represents absorber conditions where the liquid leaving the absorber is saturated with the pollutant and can no longer absorb any additional pollutant, unless more liquid is added.
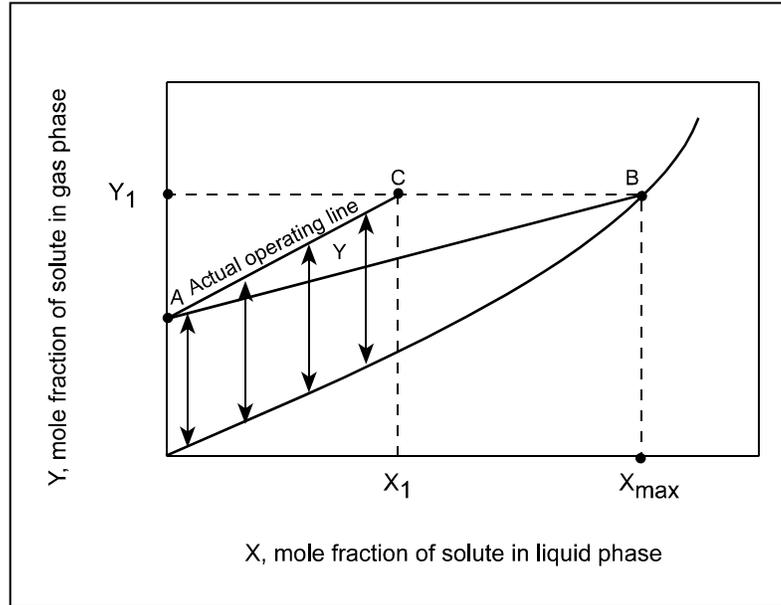
Part 4

18. **a. 50 to 75%**
    In designing a packed tower, the normal practice is to make the tower diameter so that the unit will operate at 50 to 75% of the flooding velocity rate.

19. **True**
    The Sherwood correlation can be used to calculate the tower diameter of a packed tower, if the minimum liquid rate, L_m, and the gas flow rate, G, through the absorber are known.

20. **a. Transfer units**
    In estimating packing height in a packed tower, the packing sections are broken up into discrete sections called transfer units.

21. **HTU = height of a transfer unit**
    NTU = number of transfer units
    In the equation, $Z = HTU \times NTU$, which estimates the packing height, Z:

    HTU = height of a transfer unit
    NTU = number of transfer units

_____

22. **True**
   The Colburn diagram can be used to estimate the number of transfer units based on an overall gas-film coefficient, N_{OG}, if the absorption factor (mG_m/L_m), the inlet and outlet pollutant concentrations, and the liquid recycle concentrations are known. See Figure 11-14.

23. **e.   All of the above**
   The height of a transfer unit is a function of the following:
   - Type of packing
   - Liquid and gas flow rates
   - Pollutant concentration and solubility
   - Liquid properties and system temperature

24. **b.   0.3 to 1.2 m (1 to 4 ft)**
   For most packed tower applications, the height of a transfer unit can be estimated to be 0.3 to 1.2 m (1 to 4 ft).

Part 5

25. **c.   Priming**
   In a plate tower, if the gas velocity through the tower is too fast, liquid droplets become entrained in the gas stream, causing a condition called priming.

26. **True**
   For the purpose of determining a plate-tower diameter, priming in a plate tower is the same as the flooding point in a packed tower.

27. **c.   Number of theoretical plates**
   In a plate tower, the following equation:

$$N_p = \frac{\ln\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{\ln\left(\dfrac{L_m}{mG_m}\right)}$$

   is used to calculate the number of theoretical plates.

28. **b.   65 to 80%**
   In plate towers, the efficiency of each plate, or tray, is usually 65 to 80%.

_____

Solution to Problem 1

Answer: To achieve the required removal efficiency, the operating liquid flow rate, Q_L, should equal **123 gal/min**.

Solution:

1. **Determine mole fraction of HCl in gas and liquid phases**. (See Appendix A for help converting from ppm to mole fractions.)

    Given: Y_1 (gas in)   =   1,000 ppm or 0.001 mole fraction
                    Y_2 (gas out)   =   30 ppm or 0.00003 mole fraction
                    X_2 (liquid in)   =   0 ppm
                    X_1 (liquid out)   =   unknown
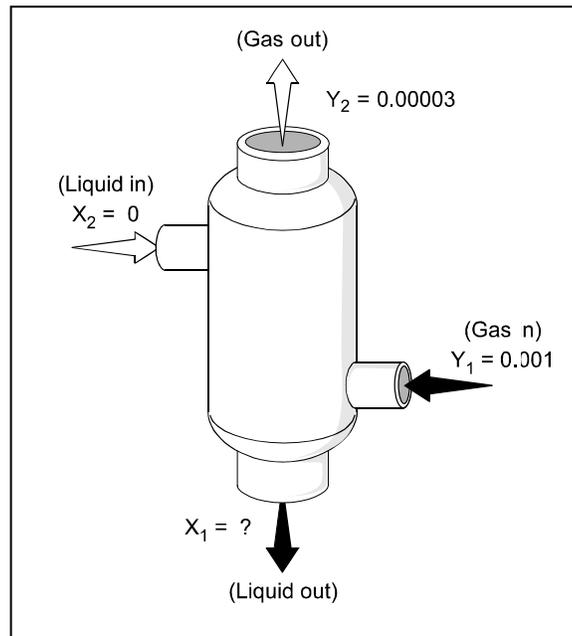
2. **Convert gas flow, Q_G, from acfm to molar units (G_m).**

    $$G_m = Q_G \quad \times \quad \text{temperature correction} \quad \times \quad R$$
    $$\text{to standard (in absolute units)}$$

    $$G_m = 15,000 \, \frac{\text{acf}}{\text{min}} \times \frac{460 + 70}{460 + 500} \times \frac{\text{lb - mole}}{380 \, \text{scf}}$$
    $$= 21.8 \, \text{lb - mole/min}$$

3. **Calculate the concentration of HCl in the existing liquid (X_1) at the minimum flow rate**. At the minimum liquid flow rate, the gas mole fraction of HCl entering the absorber, Y_1, will be in equilibrium with the liquid mole fraction leaving the absorber, X_1. At equilibrium:

$$Y_1 = m X_1$$
$$X_1 = Y_1/m$$

Given: $\quad m = 1.1$, Henry's law equilibrium constant

$$X_1 = (0.001)/1.1$$
$$X_1 = 0.00091$$

4. **Compute the minimum L_m/G_m** using the following equation:

$$Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$$

$$0.001 - 0.00003 = \left(\frac{L_m}{G_m}\right)_{min}(0.00091 - 0)$$

$$1.07 = \left(\frac{L_m}{G_m}\right)_{min}$$

5. **Calculate the minimum liquid flow rate, in gallons per minute**.

$$(L_m/G_m)_{min} = 1.07$$
$$(L_m)_{min} = G_m(1.07)$$

From step 2: $\quad G_m = 21.8$ lb-mole/min

$$(L_m)_{min} = (21.8 \text{ lb-mole/min}) \, 1.07$$
$$= 37 \text{ lb-mole/min}$$

Convert from molar flow rate $\left(\dfrac{\text{lb - mole}}{\text{min}}\right)$ to volumetric flow rate (gal/min).

$$\text{min imum } Q_L = \frac{37 \text{ lb - mole}}{\text{min}} \times \frac{18 \text{ lb}}{\text{lb - mole}} \times \frac{\text{gal}}{8.35 \text{ lb}}$$
$$= 82 \text{ gal / min}$$

_____

6. **Calculate operating liquid flow rate, Q_L.**

Operating Q_L = 1.5 $\times$ minimum liquid flow rate

= 1.5 $\times$ 82 gal / min

= 123 gal / min

_____

Solution to Problem 2

Answer: **No, the existing tower (as is) cannot accommodate additional flows.**

Solution:

1. **Convert the proposed gas and liquid volumetric flow rates to mass units.**

   Given: Q_G = 12,500 acfm at 70° F

   $$G = 12,500 \frac{ft^3}{min} \times \frac{lb\text{-}mole}{380\ ft^3} \times \frac{29\ lb}{lb\text{-}mole}$$

   $$= 954\ lb\,/\,min$$

   Given: Q_L = 125 gal / min

   $$L = 125 \frac{gal}{min} \times \frac{0.134\ ft^3}{gal} \times \frac{64\ lb}{ft^3}$$

   $$= 1,072\ lb\,/\,min$$

2. **Calculate the abscissa in the flooding curve.**

   Use equation 11-16:

   $$\text{Abscissa} = \frac{L}{G} \times \left(\frac{\rho_g}{\rho_l} \right)^{0.5}$$

   Given:
   $$\rho_g = 0.075\ lb/ft^3, \text{ the density of gas}$$
   $$\rho_l = 64\ lb/ft^3, \text{ the density of liquid}$$

   From step 1:
   $$L = 1.072\ lb/min$$
   $$G = 954\ lb/min$$

   $$\text{Abscissa} = \left(\frac{1{,}072\ lb/min}{954\ lb/min} \right) \left(\frac{0.075\ lb/ft^3}{64\ lb/ft^3} \right)^{0.5}$$

   $$= 0.038$$

3. **Calculate the area of the tower** using one of the following two equations.

   $$A = \pi r^2$$

   $$A = 0.7854 \times d^2$$

_____

Where: A = area of cross-section of tower, m^2 (ft^2)

                r = radius of tower, m (ft)

                d = diameter of tower, m (ft)

Given: d = 4 ft

$$A = (0.7854)(4 \text{ ft})^2$$

$$= 12.56 \text{ ft}^2$$

4. **Next, calculate the superficial gas velocity (G').**

$$G' = G/A$$

From step 1: G = 954 lb/min

From step 3: A = 12.56 ft^2

$$G' = \frac{954 \text{ lb}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{1}{12.56 \text{ ft}^2}$$

$$= 1.27 \text{ lb}/\text{sec} \bullet \text{ft}^2$$

5. **Calculate ε, the ordinate in the flooding curve.**

$$\varepsilon = \frac{G'^2 F \phi \, \mu_l^{0.2}}{\rho_g \rho_l g_c}$$

Given: F = 45 ft^3, packing factor

             ϕ = 1.01, ratio of the specific gravity of scrubbing liquid to that of water

             μ_l = 0.018 centipoise, viscosity of liquid

             ρ_g = 0.075 lb/ft^3, the density of gas

             ρ_l = 64 lb/ft^3, the density of liquid

             g_c = 32.2 lb/sec^2, the gravitational constant

From step 4: G' = 1.27 lb/sec•ft^2

$$\varepsilon = \frac{\left(1.27 \text{ lb}/\text{sec} \bullet \text{ft}^2\right)^2 \left(45 \text{ ft}^3\right)(1.01)(0.018 \text{ centipoise})^{0.2}}{\left(0.075 \text{ lb}/\text{ft}^3\right)\left(64 \text{ lb}/\text{ft}^3\right)\left(32.2 \text{ lb}/\text{sec}^2\right)}$$

$$= 0.21$$

From the coordinates on the graph in Figure 11-11, the new operating point (x = 0.038 and y = 0.21) would be above the flooding line and this is unacceptable. Note that the facility could still increase throughput and utilize the same tower by switching to a different packing material with a lower packing factor. For example, by using 2 inch plastic Tellerettes with a factor (F) of 20, the new ε would be 0.09 which would be well within acceptable limits.

_____

Solution to Problem 3

Answer: **Number of theoretical plates = 6.08**
             Total height of column = 20 ft

Solution:

1. **Convert gas and liquid volumetric flow rates (Q_G and Q_L) to molar units (G_m and L_m).**

$$G_m = Q_G \quad \times \quad \begin{array}{c} \text{temperature correction} \\ \text{to standard (in absolute units)} \end{array} \quad \times \quad R$$

$$G_m = \frac{15{,}000 \text{ acf}}{\text{min}} \times \frac{460 + 70}{460 + 500} \times \frac{\text{lb - mole}}{380 \text{ scf}}$$

$$= 21.8 \text{ lb - mole / min}$$

$$L_m = \frac{123 \text{ gal}}{\text{min}} \times \frac{8.35 \text{ lb}}{\text{gal}} \times \frac{\text{lb - mole}}{18 \text{ lb}}$$

$$= 57 \text{ lb - mole / min}$$

2. **Calculate number of theoretical plates, N_p.**

$$N_p = \frac{\ln\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{\ln\left(\dfrac{L_m}{mG_m}\right)}$$

Given: Y_1 (inlet gas)   =   0.01 mole fraction
          Y_2 (outlet gas) =   0.00003 mole fraction
          X_2 =   0, concentration of HCI in inlet liquid
          m   =   1.1, Henry's law equilibrium constant

From step 1: G_m =   21.8 lb-mole/min
               L_m =   57 lb-mole/min

_____

$$N_p = \frac{\ln\left[\left(\dfrac{0.01-0}{0.00003-0}\right)\left(1-\dfrac{(1.1)(21.8)}{57}\right)+\dfrac{(1.1)(21.8)}{57}\right]}{\ln\left(\dfrac{57}{(1.1)(21.8)}\right)}$$

$$= \frac{\ln 193.52}{\ln 2.37}$$

$$= 6.08 \text{ theoretical plates}$$

3. **Calculate the number of actual plates.**

$$\text{Actual plates} = \frac{\text{estimated theoretical plates}}{\text{overall efficiency}}$$

Given: overall tray efficiency = 70%

From step 2:   estimated number of theoretical plates = 6.08

Actual plates =   6.08/0.70
            =   8.7 plates
            =   9 plates (since you can't have a fractional plate)

4. **Estimate the height of the tower, Z.**

$$Z = (\text{Number plates}) \times (\text{tray spacing}) + \text{top spacing}$$

Given: tray spacing = 2 ft
             top spacing = 2 ft

From step 3:   number of actual plates = 9

$$Z = (9 \times 2 \text{ ft}) + 2 \text{ ft}$$
$$Z = 20 \text{ ft}$$

Note this is a rather tall tower for this separation. By increasing the liquid flow the tower height could be reduced. For example, by doubling the liquid flow rate the tower height could be reduced to half the size.

Bibliography

Bethea, R. M. 1978. *Air Pollution Control Technology*. New York: Van Nostrand Reinhold.

Bhatia, M. V. 1977. Packed tower and absorption design. In P. N. Cheremisinoff and R. A. Young (Eds.), *Air Pollution Control and Design Handbook*. New York: Marcel Dekker.

Calvert, S., J. Goldschmid, D. Leith, and D. Mehta. 1972, August. *Wet Scrubber System Study*. Vol. 1, *Scrubber Handbook*. EPA-R2-72-118a. U.S. Environmental Protection Agency.

Danckwerts, P. V. 1951. *Industrial and Engineering Chemistry*. 43:1460.

Diab, Y. S., and R. N. Maddox. 1982. Absorption. *Chemical Engineering*. 89:38-56.

Higbie, R. 1935. *Transactions of AIChE*. 31:365.

MacDonald, J. W. 1977. Packed wet scrubbers. In P. N. Cheremisinoff and R. A. Young (Eds.), *Air Pollution Control and Design Handbook*. Part 2. New York: Marcel Dekker.

Marchello, J. M. 1976. *Control of Air Pollution Sources*. New York: Marcel Dekker.

McCabe, W. L., and C. J. Smith. 1967. *Unit Operations of Chemical Engineering*. New York: McGraw-Hill.

Perry, J. H. (Ed.). 1973. *Chemical Engineers' Handbook*. 5th ed. New York: McGraw-Hill.

Richards, J. R. 1995. *Control of Gaseous Emissions*. (APTI Course 415). U.S. Environmental Protection Agency.

Sherwood, K. T. and R. L. Pigford. 1952. *Absorption and Extraction*. New York: McGraw-Hill.

Theodore, L., and A. J. Buonicore. 1975. *Industrial Control Equipment for Gaseous Pollutants*. Vol. I. Cleveland: CRC Press.

Toor, H. L., and J. M. Marchello. 1958. *Journal of AIChE*. 4:97.

Treybal, R. E. 1968. *Mass Transfer Operations*. 2nd ed. New York: McGraw-Hill.

Whitman, W. G. 1923. *Chemical and Metallurgical Engineering*. 29:147.

Zenz, F. A. 1972. Designing gas absorption towers. *Chemical Engineering*. 79:120-138.

Appendix A

Mole Fraction and Part Per Million (ppm)

The **mole fraction** is simply an expression of the number of moles of a compound divided by the total number of moles of all the compounds present in the gas. For ideal gases (most air pollution control situations) the mole fraction is an alternative way of expressing the volume percent. For example, assume a container holds 2 pound moles of ambient air, and the composition is 79% molecular nitrogen, 20.9% molecular oxygen, and 0.1% other compounds. The mole fraction of molecular nitrogen would be 0.79, and the mole fraction of molecular oxygen would be 0.209.

The **part per million** by volume (ppm v/v or simply ppm) format is a useful means of expressing the concentrations of pollutants present at low concentrations. It is defined in the equations below:

$$\text{ppm of compound i} = \text{mole fraction}_{(compound\ i)} \times 10^6 \qquad \textbf{A-1}$$

$$\text{ppm of compound i} = \frac{\text{moles}_{(compound\ i)} \times 10^6}{\text{moles}_{(total)}} \qquad \textbf{A-2}$$

$$\text{ppm of compound i} = \frac{\text{volume}_{(compound\ i)} \times 10^6}{\text{volume}_{(total)}} \qquad \textbf{A-3}$$

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